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COST/BENEFIT TRADEOFFS FOR REDUCING THE ENERGY CONSUMPTION OF THE COMMERCIAL AIR TRANSPORTATION SYSTEM

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SUMMARY REPORT

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DOUGLAS AIRCRAFT COMPANY
MCDONNELL DOUGLAS CORPORATION
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COST/BENEFIT TRADEOFFS FOR REDUCING THE ENERGY CONSUMPTION OF THE COMMERCIAL AIR TRANSPORTATION SYSTEM

SUMMARY REPORT

by

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PREFACE

This report was prepared by the Douglas Aircraft Company, McDonnell Douglas Corporation, under NASA Contract NAS2-8618 for a study of the "Cost/Benefit Tradeoffs for Reducing the Energy Consumption of the Commercial Air Transportation System." The study, hereafter referred to as the RECAT Study (Reduced Energy for Commercial Air Transportation), was performed from November 5, 1974 to June 30, 1976.

The NASA Technical Monitor for the RECAT Study was Louis J. Williams, Research Aircraft Technology Office, Ames Research Center, Moffett Field, California.

The Douglas Study Team consisted of Emmett F. Kraus, responsible for Technical Analyses, assisted by Melvin A. Sousa, responsible for Turboprop Aircraft Analysis; and June C. Van Abkoude, responsible for Market and Economic Analyses, assisted by Clayton R. Sturdevant.

Appreciation for their cooperation and contribution is extended to the RECAT Study co-contractors: Lockheed-California Company, United Air Lines and United Technologies Research Center. Appreciation is also extended to the Hamilton Standard Division of United Technologies Corporation for assistance in preparation of propfan propulsion data.

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SYMBOLS AND ABBREVIATIONS

ABR	Abreast
A/C	Aircraft
ALT	Altitude
ASM	Available Seat-Mile
ASNM	Available Seat-Nautical Mile
ATA	Air Transport Association
ATC	Air Traffic Control
AVG	Average
BTU	British Thermal Unit
CAB	Civil Aeronautics Board
CG	Center of Gravity
CONSER	Conserving
dB	Decibel
DEG	Degree
DERIV	Derivative
DOC	Direct Operating Cost
DOC_{15}	Optimization Parameter: Minimum DOC @ 15 Cents per Gallon Fuel
DOC_{30}	Optimization Parameter: Minimum DOC @ 30 Cents per Gallon Fuel
DOC_{60}	Optimization Parameter: Minimum DOC @ 60 Cents per Gallon Fuel
Δ	Incremental Parameter Change
ENG	Engine
EPNdB	Unit of Effective Perceived Noise Level
EPNL	Effective Perceived Noise Level, EPNdB
EXIST	Existing
FAR	Federal Air Regulation
FLT	Flight
fps	Feet per Second
FT	Feet
4-D RNAV	Four-Dimensional Area Navigation
GAL	Gallon
HR	Hour
HUBS	Hub-Constrained Airports
IMPR	Improved
INC	Increased
IOC	Indirect Operating Cost
KEAS	Knots Equivalent Air Speed
KT	Knot
LB	Pound
LBM	Mass in Pounds
L.F.	Load Factor
M	Mach Number
MAX	Maximum
MF	Optimization Parameter: Minimum Fuel
MIN	Minimum
min	Minutes
MOD	Aircraft Modification or Retrofit Option
NASA	National Aeronautics and Space Administration
NM	Nautical Mile
NO.	Number
N80	New Near-Term Aircraft: NASA Specification, 1980 Introduction Date

OEW	Operational Empty Weight
OPER	Operations
PASAP	Passenger Aircraft Sizing and Performance Program
PSGR	Passenger
RECAT	Reduced Energy for Commercial Air Transportation
RPM	Revenue Passenger-Mile
SCW	Supercritical Wing
SFC	Specific Fuel Consumption
SL	Sea Level
SLS	Sea Level Static
SQ	Square
STD	Standard
TOC	Total Operating Cost
TOGW	Takeoff Gross Weight
TSFC	Thrust-Specific Fuel Consumption
TSLS	Thrust-Sea Level Static
VOR	Very High Frequency Omni-Directional Radio

UNITS CONVERSION TABLE:

TO CONVERT	MULTIPLY BY
degree to radian	1.745×10^{-2}
foot to meter	0.3048
foot^2 to meter^2	0.0929
gallon to meter^3	3.785×10^{-3}
inch to meter	2.540×10^{-2}
knot to meter/second	0.5144
nautical mile to meter	1852
pound-force to Newton	4.448
pound-mass to kilogram	0.4536

SUMMARY

The purpose of this study was to examine and compare the fuel saving potential and cost effectiveness of numerous operational and technical options proposed for reducing the fuel consumption of the U.S. commercial airline fleet. Another objective was to determine the impact of the most promising fuel conserving options on fuel consumption, passenger demand, operating costs and airline profits when implemented in the U.S. domestic and international airline fleets. Additionally, an estimate was made of the potential fuel savings achievable in the U.S. scheduled air transportation system over the forecast period, 1973-1990.

The study was divided into three parts. Part I, the primary study, investigated the means for reducing the jet fuel consumption of the U.S. scheduled airlines in domestic passenger operations. Part II concentrated on the design and examination of two turboprop aircraft as possible fuel conserving derivatives of the DC-9-30. Part III extended the primary study in Part I to include the international operations of the U.S. scheduled carriers.

Part I: Study of the U.S. Domestic Air Transportation System

The technical possibilities for reducing aircraft and system fuel consumption by means of operational changes, retrofit and production modifications, derivative aircraft, and new near-term aircraft were analyzed. Seven baseline aircraft representative of Douglas jet transports in the domestic fleet were used as the bases for comparing the potential fuel savings, and later, the economic and operational viability of the aircraft options under consideration. From the technical analysis, 46 aircraft operational and design options were specified for further evaluation in the study market.

The market analysis in Part I began with an investigation of the scheduled airline operations within the U.S. domestic air transportation system and was carried out in two phases. Phase I involved the selection of a study market representative of the domestic system's characteristics, and a projection of the traffic demand in this market from 1973-1990. Phase II concerned the development of alternative fleet forecasts to screen and select the most promising fuel conserving operational and design options for the U.S. domestic airline fleets during the forecast period. Fleet requirements for and fuel savings from the selected aircraft options in the study market were then projected to the total domestic scheduled system.

The most promising fuel conserving operational procedures were based upon an improved ATC system assumed available in 1980. With an improved system, direct operating cost savings of between 3.5 to 5% were achieved for the baseline airplanes. The total potential fuel savings from both improved operating procedures and an advanced ATC were over 10% during the period 1980-1990.

Many study retrofit and production modification options were uneconomical due to high modification costs. The three most promising modification options selected by the market provided fuel savings of almost 1.5% over the forecast period, 1973-1990.

The study derivative aircraft types proved that it is economically feasible to make extensive modifications to existing aircraft for the purpose of improving seat-mile fuel economy and offered the most promising potential for reducing fuel consumption in the near-term. When the selected derivative options were added to the fleet of existing airplanes and selected mod options, fuel savings improved substantially to 7% during 1980-1990, and to nearly 8.5% in 1990 alone. Profits per RPM also increased by over 5% during 1980-1990 with the selected derivative options in the fleet.

The all-new 1980 introduction aircraft (N80's) also offered a good potential for economically reducing aircraft fuel consumption, but since their market introduction was timed so close to that of the derivatives, the all-new aircraft could not realize their full potential in the study market by 1990. Even though fuel savings of over 10% were achieved from a mixed fleet of selected aircraft options (mods, derivatives, plus N80's) over the 1980-1990 time period, the real promise of the N80's is demonstrated by the mixed fleet fuel savings of 14-15% in 1990 alone.

Part II: Analysis of DC-9 Derivative Turboprop Aircraft

Two short/medium range DC-9-30 derivative turboprop configurations were designed to show the advantages of new turboprop technology as a means of reducing aircraft fuel consumption. The turboprop airplanes were then operationally and economically compared with their turbofan counterparts.

Due to fuel savings of 27-33%, the turboprops offered DOC savings of 5-6% with fuel at 30¢ per gallon. This preliminary investigation showed that there is considerable promise in the fuel saving potential and economic viability of advanced technology turboprops in competition with turbofan aircraft in the air transportation system.

Part III: Study of the U.S. International Air Transportation System

The international operations of the U.S. scheduled airlines were also studied in order to determine the international fleet requirements and anticipated fuel demand for these carriers during the period 1974-1990. The study market included all the city-pairs outside the continental U.S. and Canada presently served by these airlines; and a total of thirteen baseline aircraft were examined as representative of the airplanes in the 1974 U.S. international fleet. The baseline fleet included Douglas, Boeing, and Lockheed airplanes. Four possible derivative aircraft as well as six all-new long range aircraft (N80's) were analyzed in terms of their economic viability and potential fuel savings relative to the baseline airplanes. The market analysis was accomplished in the same manner as for the U.S. domestic study (Part I).

When the selected derivative options were added to the fleet, at a fuel price of 30¢ per gallon, profits increased by 6% from 1976-1990 and by almost 7% from 1980-1990. Fuel savings also improved substantially, amounting to almost 6% during 1980-1990 and almost 11% in 1990 alone. None of the long-range N80 airplanes was viable in the market under any of the airline environments studied. When added to the fleet, the selected N80 options increased profits by approximately 1.5% with fuel at 30¢ per gallon, but fuel savings did not improve over that provided by the derivatives.

INTRODUCTION

In late 1973, when jet fuel prices began to increase rapidly and fuel supplies were limited, attention was focused on the air transport industry's need to increase efficiency and conserve fuel. In response, the airlines made immediate adjustments in schedules and operations, while government and industrial organizations pursued efforts to identify the most effective means of reducing present and future transport fuel requirements.

Preliminary studies indicated that changes in aircraft schedules and operations, together with the application of new technologies, could lead to fuel savings of over 50%. However, the solutions presented were often a mixture of near-term and far-term improvements, and the real costs and effectiveness of these fuel saving possibilities over time were unclear.

In November 1974, the NASA Ames Research Center contracted with Douglas Aircraft Company, Lockheed-California Company, United Airlines, and United Technologies Research Center to study the relative costs and benefits associated with near-term solutions for Reducing the Energy consumed by U.S. domestic Commercial Air Transportation (RECAT Study). The study was structured to provide interaction among the contractors in order to determine those fuel conserving options that offered the most promise for fuel conservation in the near-term. The study options and their associated costs were reviewed by the airline contractor to assure their realism and suitability for commercial airline use. Using the most promising fuel conserving options, alternative fleet forecasts were developed to establish realistic bounds for the demand for jet fuel in the U.S. domestic system through 1990.

During the course of the study, two new areas of interest developed for potential fuel conservation. The first was a specific examination of advanced turboprop aircraft, while the second was the potential for, as well as the particular problems associated with, fuel conservation for U.S. carriers operating in the international market. In November 1975, NASA contracted with the Douglas Aircraft Company to study DC-9 derivative turboprop-powered aircraft and to conduct a preliminary investigation of fuel conservation in the U.S. international market, as additional tasks to the primary RECAT Study.

The final report is presented in two volumes. Volume I describes the technical results. Volume II presents the results of the market and economic analyses.

This report contains U.S. Customary Units. Conversions to International System (SI) Units are presented with the Symbols and Abbreviations.

SECTION 1.0

DOMESTIC STUDY BASELINE AIRCRAFT

1.1 Ground Rules

The technical ground rules for the study are given in Table 1. The study interiors are dual class arrangements with approximately 10% first class seating. Seat pitch is 38 inches for first class and 34 inches for coach. The aircraft in domestic commercial passenger service actually have fewer seats because of larger first class sections and/or larger seat pitch distances. Baseline operations were chosen to be representative of minimum DOC operations used by domestic carriers prior to the 1973 fuel price increases.

TABLE 1

TECHNICAL GROUND RULES

SEATING DENSITY:	10/90 SPLIT WITH 38"/34" PITCH 8 ABREAST ON BASELINE DC-10
LOAD FACTOR:	58% FOR FUEL USE COMPARISONS 100% FOR NEW AIRPLANE SIZING
PAYLOAD:	NO CARGO CARRIED IN FUEL USE COMPARISONS 200 LB/(PSGR & BAGS) IN FUEL USE COMPARISONS
GALLEY LOCATION:	LOWER DECK, WHERE FEASIBLE
TOTAL MANEUVER TIME:	15 MINUTES
FUEL ONBOARD:	MISSION FUEL ONLY (INCLUDES RESERVES) DENSITY = 6.8 LBM/GALLON HEAT CONTENT = 18,600 BTU/LBM

1.2 Baseline Aircraft

Passenger versions of Douglas commercial transports used in the domestic fleet were chosen as baseline aircraft. These include aircraft from the following families: DC-8-20, DC-8-50, DC-8-60, DC-9-10, DC-9-30, DC-10-10, and DC-10-40. Each aircraft family is comprised of several models. The most common model in domestic passenger service was chosen as the baseline aircraft for each family. The seven study baseline models and their characteristics are given in Table 2. The general characteristics of the airplanes are based on actual delivered aircraft. Weight adjustments were included to reflect the study baseline interiors.

Payload-range envelopes for the baseline airplanes are given in Figure 1. The study baseline aircraft cover a broad range of capabilities. Figure 2 shows the comparison of available seat-nautical miles per gallon for the baseline airplanes. The curves of Figure 2 are based on engineering handbook performance data. Consequently, they are representative of new aircraft on the idealized study flight profile in zero wind conditions. In practice, airlines actually experience greater air hold and ground delay times, clearances to non-optimum altitudes, winds, high temperatures, engine and airframe performance deterioration, and excess fuel loads. These factors, together with lower seating densities, lead to lower actual seat-mile fuel efficiency than indicated by handbook data. Fuel consumption reported by the airlines to the Civil Aeronautics Board (CAB) is given for comparison in Figure 2 at the 1973 CAB average stage length for each aircraft. Actual aircraft fuel efficiency, in terms of seat-nautical miles per gallon, is a weighted average of 30.2% below the values derived for ideal conditions at the CAB average stage lengths.

TABLE 2

BASELINE AIRCRAFT CHARACTERISTICS

AIRCRAFT MODEL		DC-8-21	DC-8-52	DC-8-61	DC-9-15	DC-9-32	DC-10-10	DC-10-40
ENGINES: NUMBER		4	4	4	2	2	3	3
TYPE		JT4A-9	JT3D-3B	JT3D-3B	JT8D-7	JT8D-7	CF6-6D	JT9D-20
SLS THRUST/ENGINE	(LB)	16,800	18,000	18,000	14,000	14,000	40,100	49,400
NUMBER OF PSGRS., 10/90% SPLIT, 38/34" PITCH		146	146	203	70	92	277*	252
HIGH SPEED CRUISE MACH NUMBER		.83	.82	.82	.80	.80	.85	.85
MAXIMUM RANGE: @ 100% LOAD FACTOR, HIGH SPEED CRUISE	(NM)	2,670	4,200	3,260	1,360	1,220	3,410	5,020
@ 58% LOAD FACTOR, HIGH SPEED CRUISE	(NM)	3,060	4,800	3,560	1,420	1,310	3,880	5,560
1973 CAB AVERAGE STAGE LENGTH	(NM)	862	731	800	300	290	870	670
MAXIMUM TAKEOFF DISTANCE, SL, STD DAY	(FT)	8,050	8,940	10,480	6,480	5,530	8,840	12,340
APPROACH SPEED AT STUDY LANDING WEIGHT, STD DAY	(KT)	121	120	128	116	111	121	132
WING AREA	(FT^2)	2,773	2,881	2,884	934	1,001	3,550	3,647
WING SPAN	(FT)	142.4	142.4	142.4	89.4	93.4	155.3	165.3
MAXIMUM TAKEOFF WEIGHT	(LB)	276,000	300,000	325,000	90,700	108,000	430,000	555,000
MAXIMUM LANDING WEIGHT	(LB)	193,000	202,000	240,000	81,700	99,000	363,500	403,000
STUDY LANDING WEIGHT	(LB)	171,300	167,830	192,230	63,390	74,090	285,870	319,770
OPERATORS EMPTY WEIGHT	(LB)	137,900	138,430	156,100	49,840	57,900	237,240	270,910
STUDY PAYLOAD, 58% LOAD FACTOR @ 200 LB/PSGR AND BAG	(LB)	17,000	17,000	23,600	8,200	10,600	32,200	29,200
FUEL CAPACITY	(GAL)	17,550	17,900	17,900	3,679	3,679	21,763	36,522
FUEL USE WITH STUDY PAYLOAD AT 1973 CAB AVERAGE STAGE LENGTH	($\frac{LB}{ASNM}$)	0.224	0.185	0.144	0.225	0.184	0.125	0.161
1973 DOC AT 1973 CAB AVERAGE STAGE LENGTH, 30¢/GAL FUEL PRICE	($\frac{¢}{ASNM}$)	2.029	1.961	1.495	2.803	2.309	1.403	1.846

*Lower Galley

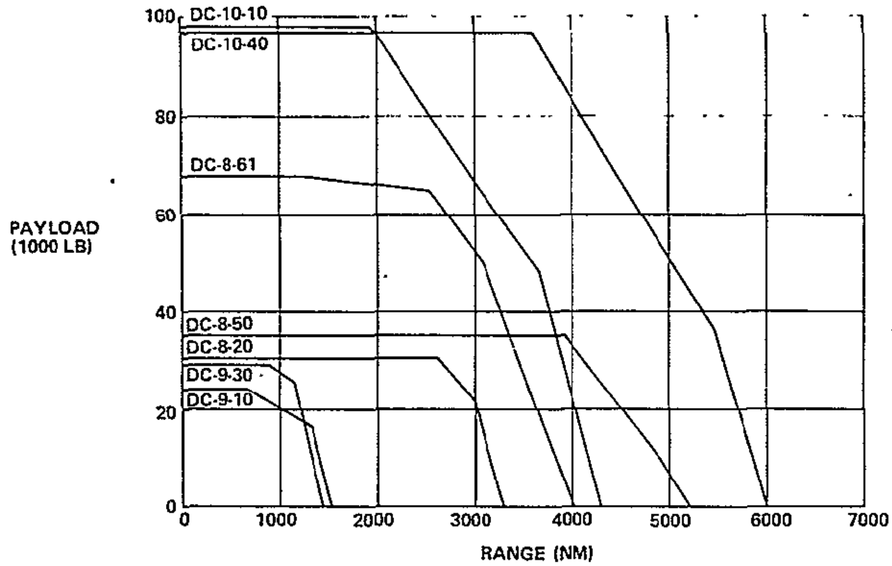
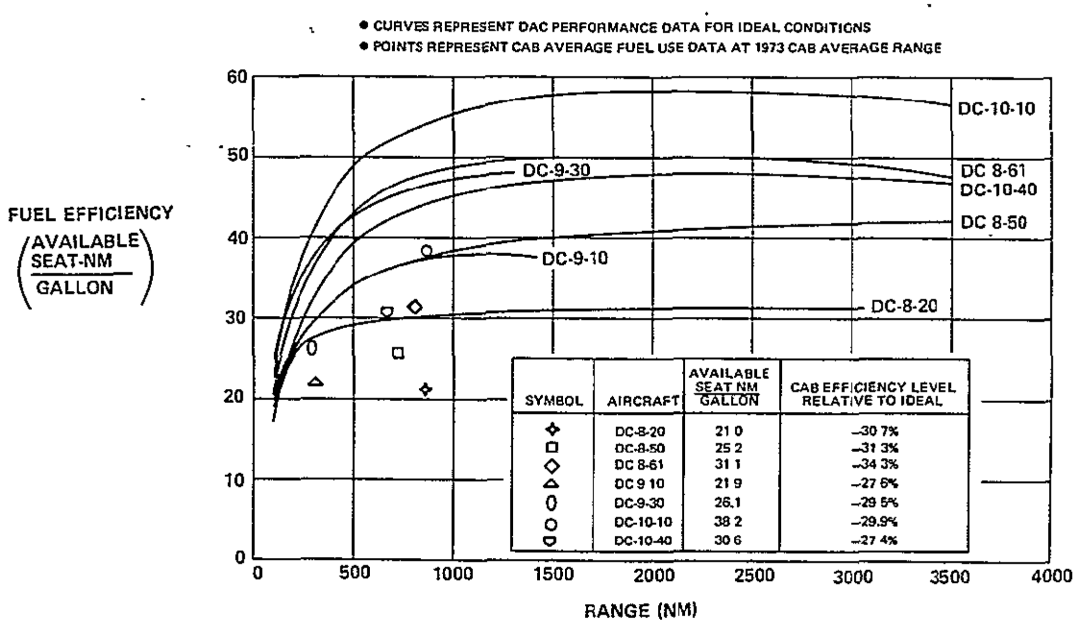


FIGURE 1. BASELINE AIRCRAFT PAYLOAD-RANGE COMPARISON



SYMBOL	AIRCRAFT	AVAILABLE SEAT NM / GALLON	CAB EFFICIENCY LEVEL RELATIVE TO IDEAL
✦	DC-8-20	21 0	–30 7%
□	DC-8-50	25 2	–31 3%
◇	DC 8-61	31 1	–34 3%
△	DC 9 10	21 9	–27 6%
0	DC-9-30	26.1	–29 5%
○	DC-10-10	38 2	–29.9%
▽	DC-10-40	30 6	–27 4%

FIGURE 2. BASELINE AIRCRAFT FUEL EFFICIENCY COMPARISON

SECTION 2.0

ALTERNATIVE OPERATING PROCEDURES

Fuel-conservative operating procedures are the most effective means of immediately saving fuel. Operations cover the total range of activity from the preliminary flight planning to the engine shutdown at the destination, and even include airline policy items such as average load factor and seating density. These operational variations were divided into two categories, flight operations and airline operations. Flight operations include aircraft climb and descent profiles, cruise profiles, navigational procedures, and maneuvers and delays. Airline operations include choice of load factor, seating density, maintenance standards, and center of gravity location.

2.1 Operating Procedures Selected for Study

The study flight and airline operational variations are compared to the baseline operations in Table 3. Some alternative flight operations, such as cruise climb and 4-D RNAV require an advanced ATC system for their implementation.

The effect of 4-D RNAV in an advanced ATC environment is twofold: 1) it permits an average 0.5% reduction in flight distance due to direct routing, and 2) it allows precise departure and enroute scheduling, which is credited with an average 5 minute reduction in delay and maneuver time.

The effect of fuel-conservative flight profiles, relative to the baseline flight profile, is given in Table 4. The fuel-conservative profile in the current ATC system includes long-range operations in climb, cruise and descent. For an advanced ATC system, the fuel-conservative profile also includes cruise climb or 2,000 foot steps and use of 4-D RNAV.

Fuel-conservative operations in the current ATC system reduce fuel use by about 4 to 8%, depending on the aircraft. Block fuel savings are substantially improved by upgrading the ATC system, becoming 8 to 11%. An additional benefit of advanced ATC is the reduction in DOC's. With the current ATC system, fuel-saving flight profiles result in lower speeds which increase block time and DOC's. The assumed delay time reduction in the advanced ATC system reduces overall block time and, together with fuel savings, decreases DOC's.

Seating density changes were made by removing the first class sections of the baseline configurations and converting to all coach interiors at 34-inch seat pitch. To show the effect of even higher density seating arrangements, the DC-10-40 interior was also changed from 8 to 9 abreast. Table 5 shows the baseline and high density seating capacities for the study baseline airplanes.

The effects of increased seating density are given in Table 6 at the 1973 CAB average stage length for each aircraft. Fuel use per seat-mile is reduced 7 to 13%, depending on the aircraft. The large differences between the DC-10-10 and DC-10-40 fuel and DOC savings are due to the differences in both baseline and high density interiors.

TABLE 3

OPERATIONAL VARIATIONS

	OPERATIONAL ITEM	BASELINE OPERATION	FUEL - CONSERVATIVE OPERATION	
			CURRENT ATC	ADVANCED ATC
FLIGHT OPERATIONS	CLIMB AND DESCENT PROFILES	HIGH SPEED PROFILES	LONG RANGE PROFILES	LONG RANGE PROFILES
	CRUISE ALTITUDE	4000' STEP ALTITUDE WHEN APPROPRIATE	4000' STEP ALTITUDE WHEN APPROPRIATE	2000' STEP ALTITUDE WHEN APPROPRIATE, OR CRUISE CLIMB
	CRUISE SPEED	HIGH SPEED CRUISE MACH NUMBER (A)	LONG RANGE CRUISE @ 99% MAX NM/LB	LONG RANGE CRUISE @ 99% MAX NM/LB
	NAVIGATION	VOR	VOR	4-D RNAV
	MANEUVER & DELAY TIME	15 MINUTES	15 MINUTES	10 MINUTES
AIRLINE OPERATIONS	LOAD FACTOR	58%	65%	65%
	SEATING DENSITY	10/90 SPLIT, 38"/34" PITCH	ALL COACH, 34" PITCH	ALL COACH, 34" PITCH
	MAINTENANCE STANDARDS	MAINTAIN SAFETY, RELIABILITY, AND APPEARANCE (B)	ALSO MAINTAIN CLOSER TOLERANCES ON ENGINE AND AERODYNAMIC PERFORMANCE	ALSO MAINTAIN CLOSER TOLERANCES ON ENGINE AND AERODYNAMIC PERFORMANCE
	C.G. LOCATION	TARGET C.G. APPROXIMATELY 1-3% FORWARD OF MOST AFT C.G. LOCATION POSSIBLE (B)	MOVE C.G. AFT 1%	MOVE C.G. AFT 1%

A SEE TABLE 2

B IN-SERVICE OPERATION, NOT STUDY BASELINE

TABLE 4

EFFECT OF FUEL-CONSERVATIVE FLIGHT OPERATIONS
ON BLOCK FUEL AND DOC
AT 1973 CAB AVERAGE STAGE LENGTH

AIRCRAFT	FUEL-CONSERVATIVE FLIGHT PROFILE (1) CURRENT ATC				FUEL-CONSERVATIVE FLIGHT PROFILE (2) ADVANCED ATC			
	ΔBLOCK FUEL $\left(\% \frac{BTU}{ASNM}\right)$	ΔDOC $\left(\% \frac{¢}{ASNM}\right)$ @ 15¢/GAL	ΔDOC @ 30¢/GAL	ΔDOC @ 60¢/GAL	ΔBLOCK FUEL $\left(\% \frac{BTU}{ASNM}\right)$	ΔDOC $\left(\% \frac{¢}{ASNM}\right)$ @ 15¢/GAL	ΔDOC @ 30¢/GAL	ΔDOC @ 60¢/GAL
DC-8-20	-4.96	4.70	2.30	-0.10	-9.57	-0.28	-2.58	-4.89
DC-8-50	-4.44	5.54	3.42	1.08	-8.42	0.57	-1.34	-3.44
DC-8-61	-4.84	5.40	3.20	0.78	-9.11	0.38	-1.65	-3.90
DC-9-10	-8.19	5.04	2.71	-0.13	-10.98	0.57	-1.46	-3.99
DC-9-30	-7.86	3.53	1.56	-0.83	-9.85	-0.63	-2.30	-4.28
DC-10-10	-6.42	2.94	1.07	-0.97	-10.30	0.18	-1.92	-4.28
DC-10-40	-6.90	2.68	0.81	-1.35	-11.10	-0.42	-2.51	-4.92

(1) INCLUDES LONG RANGE CLIMB AND DESCENT, 4000' STEP ALTITUDE CRUISE @ 99% MAX NM/LB

(2) INCLUDES LONG RANGE CLIMB AND DESCENT, CRUISE CLIMB @ 99% MAX NM/LB, 33% (5 MIN.) REDUCTION IN DELAY AND MANEUVER TIME, 4-D RNAV.

TABLE 5

BASELINE AND HIGH DENSITY SEATING CAPACITIES

Aircraft	Baseline (10/90 split)	High Density (all coach)
DC-8-20	146	159
DC-8-50	146	159
DC-8-61	203	218
DC-9-10	70	77
DC-9-30	92	105
DC-10-10 (1)	277	293
DC-10-40	252	295 (2)

(1) lower galley, (2) 9-abreast

TABLE 6

EFFECT OF FUEL-CONSERVATIVE AIRLINE OPERATIONS
ON BLOCK FUEL AND DOC
AT 1973 CAB AVERAGE STAGE LENGTH

AIRCRAFT	INCREASED SEATING DENSITY (1)				INCREASED LOAD FACTOR (2)			
	Δ BLOCK FUEL $\left(\% \frac{BTU}{ASNM}\right)$	Δ DOC $\left(\% \frac{¢}{ASNM}\right)$			Δ BLOCK FUEL $\left(\% \frac{BTU}{RPNM}\right)$	Δ DOC $\left(\% \frac{¢}{RPNM}\right)$		
		@ 15¢/GAL	@ 30¢/GAL	@ 60¢/GAL		@ 15¢/GAL	@ 30¢/GAL	@ 60¢/GAL
DC-8-20	-7.31	-7.86	-7.74	-7.61	-9.33	-10.11	-9.96	-9.73
DC-8-50	-7.33	-7.96	-7.80	-7.70	-9.36	-10.21	-10.04	-9.86
DC-8-61	-6.14	-6.73	-6.56	-6.45	-9.38	-10.30	-10.07	-9.87
DC-9-10	-8.63	-9.00	-8.92	-8.84	-10.29	-10.77	-10.66	-10.57
DC-9-30	-11.47	-12.17	-12.04	-11.91	-10.94	-12.20	-12.08	-11.97
DC-10-10	-4.87	-5.34	-5.27	-5.15	-9.49	-11.28	-11.14	-10.94
DC-10-40	-13.06	-14.06	-13.87	-13.63	-10.06	-11.50	-11.36	-11.26

(1) CHANGE 10/90 SPLIT TO ALL TOURIST @ 34" PITCH (ON DC-10-40, ALSO CHANGE SEATS FROM 8 TO 9 ABREAST)

(2) INCREASE LOAD FACTOR FROM 58% TO 65%

The increased load factor of 65%, shown for fuel-conservative airline operations in Table 3, is close to the maximum average value that can be maintained on a fleetwide basis without leaving a significant number of passengers behind in peak travel periods. The effects of increasing load factor from 58 to 65% are shown in Table 6. The energy per passenger carried is reduced approximately 9 to 11%. The variation between aircraft is due mostly to differences in baseline configurations. Operating costs on a passenger-mile basis are improved about 10 to 12%.

Since improvements in both maintenance standards and CG location result in fuel savings, these items were included in Table 3. The objective of improved maintenance standards is to maintain aircraft efficiency closer to new aircraft levels. However, in this study no fuel saving benefit for improved maintenance is taken relative to baseline levels, because the baseline fuel consumption levels are representative of aircraft in new condition. In addition, due to the difficulty in achieving a more stringent target aft CG location, and the small potential benefits, no fuel saving credit is taken in this study for more aft loading.

Figure 3 summarizes the results of the fuel-conservative operations study. Fuel-saving operational options could be combined to give even greater savings. For example, relative to the baseline operation, the DC-10-40 shows an 11.1% improvement in fuel consumption for fuel-conservative flight profiles in an advanced ATC system and a 13.1% improvement for 9-abreast, all coach seating. Together, these options would give a fuel saving of 22.7%. The percentages combine as follows: $1-(1-.111)(1-.131) = .227$. If these improvements are combined with the 10.1% fuel reduction for increased load factor, the overall fuel saving is 30.5%. However, high seating density and high load factors together lead to reduced passenger appeal.

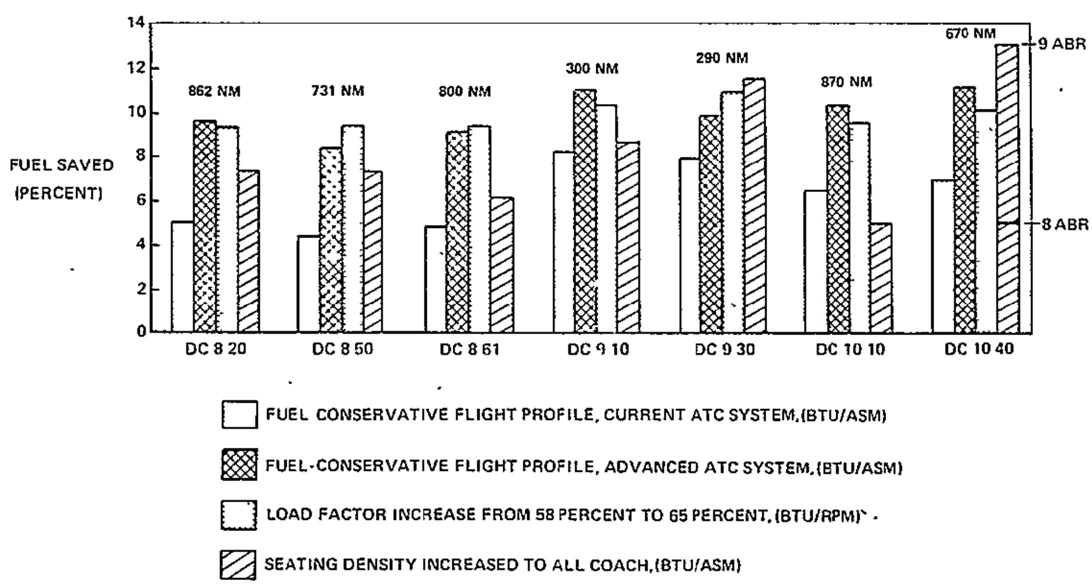


FIGURE 3. FUEL SAVED BY FUEL-CONSERVATIVE OPERATIONS

SECTION 3.0

MODIFICATION AND DERIVATIVE STUDIES

Aircraft design changes were studied in order to identify the fuel-saving potential of retrofit modifications, production modifications, and derivative airplanes. Following a sensitivity study to determine the relative value of drag, SFC, and weight improvements on each baseline airplane, a total of twenty reconfigured aircraft were proposed and analyzed.

3.1 Modification and Derivative Configurations

Table 7 presents the design changes which were combined to create twenty reconfigured study airplanes. Nomenclature for these study airplanes is also given in Table 7. The areas affected by design changes are indicated in Figure 4. General drag reduction items include aerodynamic improvements such as rerigged controls, new fairings, and reduced gaps and steps. General weight reduction items involve detail improvements of aircraft components to save weight.

TABLE 7

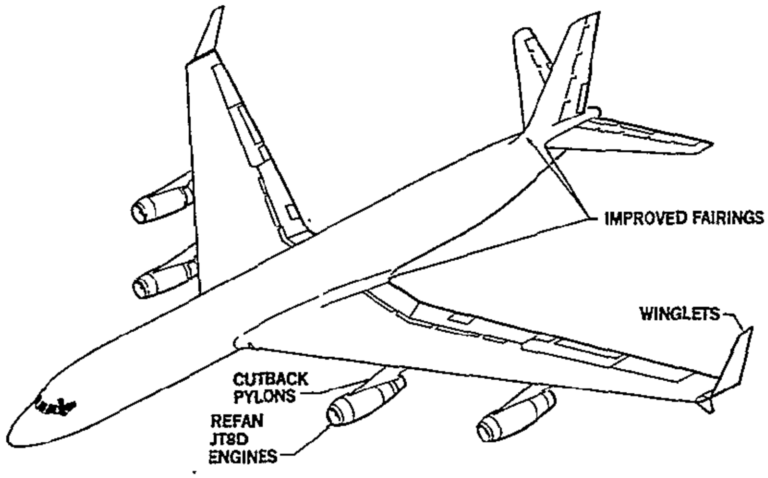
DESIGN CHANGES FOR RETROFIT, PRODUCTION MODIFIED AND DERIVATIVE AIRCRAFT

AIRCRAFT(1)	EARLIEST INTRODUCTION DATE	DESIGN CHANGE ITEM: NEW ENGINE	GENERAL DRAG REDUCTION PROGRAM	WINGLET	GENERAL WEIGHT REDUCTION PROGRAM	COMPOSITE SECONDARY STRUCTURE	STRETCH/ SHRINK	NEW SUPERCRITICAL WING
DC-8-20R	79	JT8D-209	X	X				
DC-8-20DR	78	-	X	X				
DC-8-20ER	79	JT8D-209	-	-				
DC-8-50R	79	JT8D-209(2)	X	X				
DC-8-50DR	78	-	X	X				
DC-8-50ER	79	JT8D-209(2)	-	-				
DC-8-61R	79	JT8D-209(2)	X	X				
DC-8-61DR	78	-	X	X				
DC-8-61ER	79	JT8D-209(2)	-	-				
DC-9-10R	78	-	X	X				
DC-9-30R	78	-	X	X				
DC-10-10R	78	-	X	X				
DC-10-40R	78	-	X	X				
DC-10-10M	78	-	X	X	X	X		
DC-10-40M	78	-	X	X	X	X		
DC-9-30D1	79	JT8D-17	-	X	X	X	+171"	-
DC-9-30D2	79	JT8D-209	X	-	X	X	+209"	-
DC-9-30D3	80	-	-	-	-	-	-	X
DC-10-10D	80	CF6-50	X	-	X	X	-360"	X
DC-10-40D	80	CF6-50A	X	X	X	X	+360"	-

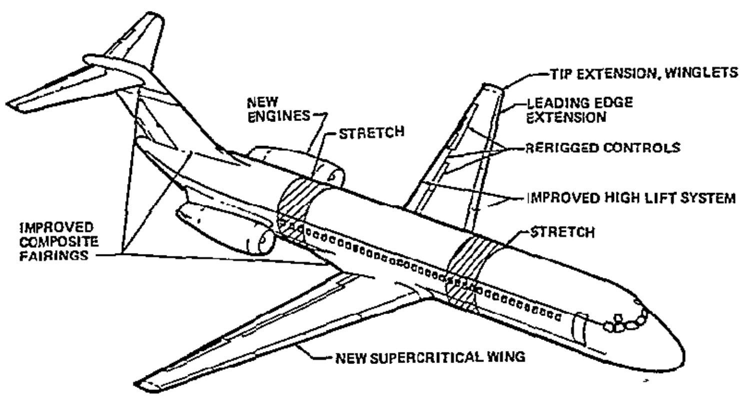
(1) AIRCRAFT DESIGNATORS:

- R = RETROFIT
- DR = DRAG (AERODYNAMIC) RETROFIT
- ER = ENGINE RETROFIT
- M = PRODUCTION MODIFICATION
- D = DERIVATIVE

(2) INCLUDES CUTBACK PYLON

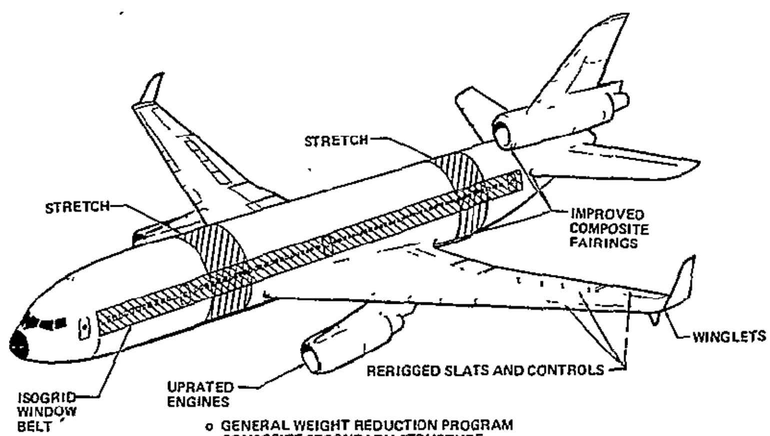


DC - 8



- o GENERAL WEIGHT REDUCTION PROGRAM
- o COMPOSITE SECONDARY STRUCTURE
  - FAIRINGS
  - WING AND TAIL TRAILING EDGES
  - FLOOR
  - DOORS

DC - 9



- o GENERAL WEIGHT REDUCTION PROGRAM
- o COMPOSITE SECONDARY STRUCTURE
  - FAIRINGS
  - TIPS
  - WING AND TAIL TRAILING EDGES
  - CONTROL SURFACES
  - FLOOR
  - GEAR DOORS

DC - 10

FIGURE 4. FUEL-CONSERVING STUDY ITEMS

Retrofit modifications were limited to engine changes and drag reduction items, including winglets. Engine retrofits were considered only for the DC-8 airplanes because properly sized replacement engines offering substantial SFC reductions are not available for the existing DC-9 and DC-10 models. The DC-8 retrofit packages were broken down into separate engine retrofit and drag retrofit packages in order to show the relative effects of these items.

Modification of production aircraft offers the possibility of structural redesign, using advanced metallics and composites to save weight. Only the DC-10 aircraft were studied for production modifications because only the DC-10-10 and DC-10-40 baseline aircraft have sufficient remaining production life to warrant substantial changes. Production has stopped on all DC-8 models and the DC-9-10 series. Production of the DC-9-30 is expected to continue for only about two years. It is being superseded by the DC-9-50.

Derivatives involve extensive changes to the baseline aircraft, such as a new wing or fuselage. Derivatives of the DC-9-30, DC-10-10, and DC-10-40 were studied, as shown in Table 7. Three derivatives are stretched airplanes, one has an unchanged fuselage length, and one is shortened. Two have new supercritical wings. Four require new engines to meet thrust requirements. Weight and/or drag reduction items are also included in the derivative designs. The DC-9-30D2 has extended wing tips, a recontoured leading edge, and an improved high lift system, in addition to the items shown in Table 7. These features improve takeoff and landing performance and reduce airplane drag.

General characteristics of these aircraft are given in Tables 8 through 11. The average stage lengths and high speed cruise Mach numbers for the modified and derivative models are the same as for their respective baselines. Maximum takeoff weights and seating capacities for production modified aircraft are also the same as their baselines. The fuel savings for the modified aircraft result in increased range capability.

The effects of the modification and derivative options on fuel use and DOC are summarized in Table 12 at the CAB average stage length. Modification options produce significant fuel use reductions but generally appear to be uneconomical at the study fuel prices. Substantial fuel benefits accrue from refan engine (JT8D-209) retrofits on the DC-8 models; but the economics of the refan retrofits are unfavorable, except for the DC-8-20R and DC-8-20ER at a fuel price of 60 cents per gallon.

The stretched derivative airplanes show substantial seat-mile fuel use reductions, ranging from 19.8% for the DC-9-30D1 to 27.9% for the DC-10-40D; and much improved DOC's due to the increased number of seats. The DC-9-30D3 involves only a new supercritical wing, but fuel use is still reduced by 4.94%, with a small reduction in operating costs at 30 cents and 60 cents per gallon. The 2.76% reduction in fuel for the DC-10-10D is remarkable because this is a shortened aircraft with fewer seats than its baseline.

The fuel-saving effects of individual and combined modification items are given in Figure 5. Figure 6 shows derivative aircraft fuel savings compared to the baseline models. The DC-10-10D is also compared to the similar-capacity DC-8-61, and shows a 19% seat-mile fuel use improvement relative to this narrow-body aircraft.

TABLE 8

MODIFIED AND DERIVATIVE AIRCRAFT CHARACTERISTICS

AIRCRAFT		DC-8-20R	DC-8-20DR	DC-8-20ER	DC-8-50R	DC-8-50DR
Maximum Takeoff Weight	(LB)	270,000	270,000	276,000	294,000	294,000
Engines: Number		4	4	4	4	4
Type		JT8D-209	JT4A-9	JT8D-209	JT8D-209	JT3D-3B
SLS Rated Thrust/Engine	(LB)	18,000	16,800	18,000	18,000	18,000
High Speed Cruise Mach Number		.83	.83	.83	.82	.82
Number of Mixed Class Passengers		146	146	146	146	146
Design Range:* @ 100% Load Factor	(NM)	3,910	2,820	3,770	5,000	4,380
@ 58% Load Factor	(NM)	4,360	3,250	4,170	5,690	5,000
Average Stage Length	(NM)	862	862	862	731	731
Fuel Use at Average Stage Length, 58% Load Factor	$(\frac{LB}{ASNM})$	0.161	0.214	0.171	0.158	0.177
1973 DOC at Average Stage Length, 30¢/Gal Fuel Price	$(\frac{¢}{ASNM})$	2.200	1.853	2.231	2.485	2.014

*At High Speed Cruise Mach Number

TABLE 9

MODIFIED AND DERIVATIVE AIRCRAFT CHARACTERISTICS

AIRCRAFT		DC-8-50ER	DC-8-61R	DC-8-61DR	DC-8-61ER	DC-9-10R
Maximum Takeoff Weight	(LB)	300,000	318,000	318,000	325,000	88,900
Engines: Number		4	4	4	4	2
Type		JT8D-209	JT8D-209	JT3D-3B	JT8D-209	JT8D-7
SLS Rated Thrust/Engine	(LB)	18,000	18,000	18,000	18,000	14,000
High Speed Cruise Mach Number		.82	.82	.82	.82	.80
Number of Mixed Class Passengers		146	203	203	203	70
Design Range:* @ 100% Load Factor	(NM)	4,820	3,850	3,420	3,700	1,440
@ 58% Load Factor	(NM)	5,480	4,200	3,750	4,050	1,520
Average Stage Length	(NM)	731	800	800	800	300
Fuel Use at Average Stage Length, 58% Load Factor	$(\frac{LB}{ASNM})$	0.166	0.122	0.137	0.129	0.216
1973 DOC at Average Stage Length, 30¢/Gal Fuel Price	$(\frac{¢}{ASNM})$	2.507	2.007	1.652	2.026	3.197

*At High Speed Cruise Mach Number

TABLE 10

MODIFIED AND DERIVATIVE AIRCRAFT CHARACTERISTICS

AIRCRAFT		DC-9-30R	DC-10-10R	DC-10-40R	DC-10-10M	DC-10-40M
Maximum Takeoff Weight	(LB)	106,000	418,000	535,000	430,000	555,000
Engines: Number		2	3	3	3	3
Type		JT8D-7	CF6-6D	JT9D-20	CF6-6D	JT9D-20
SLS Rated Thrust/Engine	(LB)	14,000	40,100	49,400	40,100	49,400
High Speed Cruise Mach Number		.80	.85	.85	.85	.85
Number of Mixed Class Passengers		92	277	252	277	252
Design Range:* @ 100% Load Factor	(NM)	1,300	3,830	5,460	4,120	5,820
@ 58% Load Factor	(NM)	1,390	4,390	6,080	4,540	6,300
Average Stage Length	(NM)	290	870	670	870	670
Fuel Use at Average Stage Length, 58% Load Factor	$(\frac{LB}{ASNM})$	0.177	0.113	0.146	0.112	0.144
1973 DOC at Average Stage Length, 30¢/Gal Fuel Price	$(\frac{¢}{ASNM})$	2.691	1.418	1.825	1.503	1.976

*At High Speed Cruise Mach Number

TABLE 11

MODIFIED AND DERIVATIVE AIRCRAFT CHARACTERISTICS

AIRCRAFT		DC-9-30D1	DC-9-30D2	DC-9-30D3	DC-10-10D	DC-10-40D
Maximum Takeoff Weight	(LB)	121,000	127,000	108,000	283,000	530,000
Engines: Number		2	2	2	2	3
Type		JT8D-17	JT8D-209	JT8D-7	CF6-50	CF6-50A
SLS Rated Thrust/Engine	(LB)	16,000	18,000	14,000	46,600	49,000
High Speed Cruise Mach Number		.80	.80	.80	.85	.85
Number of Mixed Class Passengers		117	122	92	199	327
Design Range:* @ 100% Load Factor	(NM)	1,350	1,810	1,350	2,900	4,870
@ 58% Load Factor	(NM)	1,460	1,940	1,440	3,680	5,620
Average Stage Length	(NM)	290	290	290	870	670
Fuel Use at Average Stage Length, 58% Load Factor	$(\frac{LB}{ASNM})$	0.147	0.138	0.175	0.121	0.116
1973 DOC at Average Stage Length, 30¢/Gal Fuel Price	$(\frac{¢}{ASNM})$	2.075	2.116	2.302	1.607	1.634

*At High Speed Cruise Mach Number

TABLE 12

EFFECT OF MODIFICATIONS AND DERIVATIVE DESIGNS
ON BLOCK FUEL AND DOC
AT 1973 CAB AVERAGE STAGE LENGTH

Aircraft	Δ Block Fuel (% $\frac{BTU}{ASNM}$)	Δ DOC (% ¢/ASNM)		
		@ 15¢/Gal	@ 30¢/Gal	@ 60¢/Gal
DC-8-20R	-28.25	20.50	8.43	- 3.69
DC-8-20DR	- 4.52	-10.09	- 8.67	- 7.28
DC-8-20ER	-23.73	20.96	9.96	- 1.22
DC-8-50R	-14.97	37.90	26.72	14.29
DC-8-50DR	- 4.47	4.66	2.70	0.57
DC-8-50ER	-10.50	38.16	27.84	16.44
DC-8-61R	-14.92	47.70	34.25	19.46
DC-8-61DR	- 4.53	14.57	10.50	5.99
DC-8-61ER	-10.39	48.04	35.52	21.70
DC-9-10R	- 4.06	18.01	14.06	9.27
DC-9-30R	- 3.81	20.97	16.54	11.21
DC-10-10R	- 9.07	3.65	1.07	- 1.78
DC-10-40R	- 9.32	0.81	- 1.14	- 3.47
DC-10-10M	-10.17	11.49	7.13	2.24
DC-10-40M	-10.76	11.37	7.04	2.02
DC-9-30D1	-19.80	- 8.06	-10.13	-12.68
DC-9-30D2	-24.68	- 4.85	- 8.36	-12.68
DC-9-30D3	- 4.94	0.68	- 0.30	- 1.53
DC-10-10D	- 2.76	18.88	14.54	9.64
DC-10-40D	-27.90	- 7.54	-11.48	-16.12

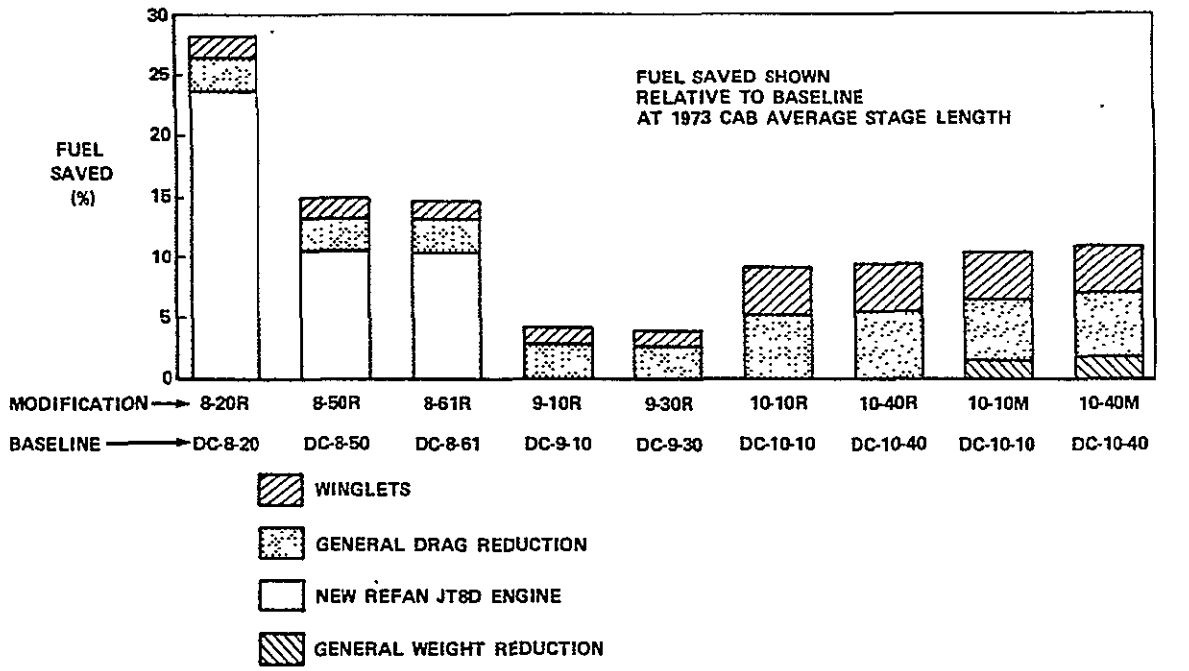


FIGURE 5. MODIFIED AIRCRAFT FUEL SAVINGS

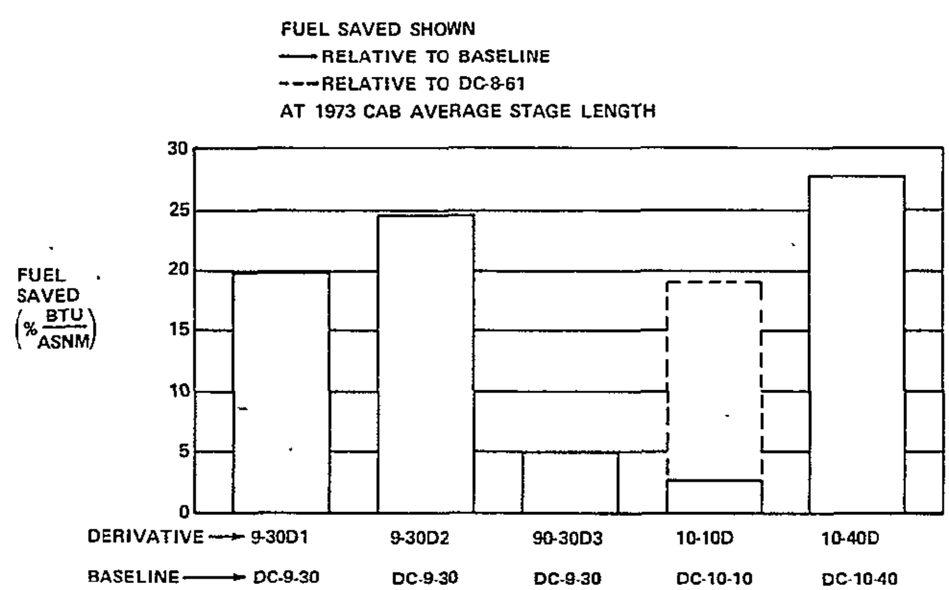


FIGURE 6. DERIVATIVE AIRCRAFT FUEL SAVINGS

SECTION 4.0

NEW NEAR-TERM AIRCRAFT

The impact of rising fuel prices on the design of new aircraft was investigated to determine whether significant improvements in fuel efficiency could be achieved. The new aircraft were designed to NASA specifications and incorporate technology consistent with a 1980 introduction date.

Five families of new aircraft were studied, three domestic range families and two international range families, resulting in eighteen optimized configurations. The domestic range families include aircraft optimized for maximum fuel efficiency and for minimum DOC at three different fuel prices, 15, 30 and 60 cents per gallon. The international range airplanes were optimized for maximum fuel efficiency and for minimum DOC at two fuel prices, 30 and 60 cents per gallon.

As a convenience, a designating code has been developed for the new near-term airplanes. For example, the 200 passenger, 1,500 nautical mile range aircraft optimized for DOC at a fuel price of 15 cents per gallon, is designated as shown in Figure 7. The subscript indicates the optimization parameter. If an aircraft was optimized for minimum fuel use, the subscript MF is used. When used without a subscript, the designator refers to an entire family of aircraft. The entire group of new near-term airplanes are referred to as N80 aircraft.

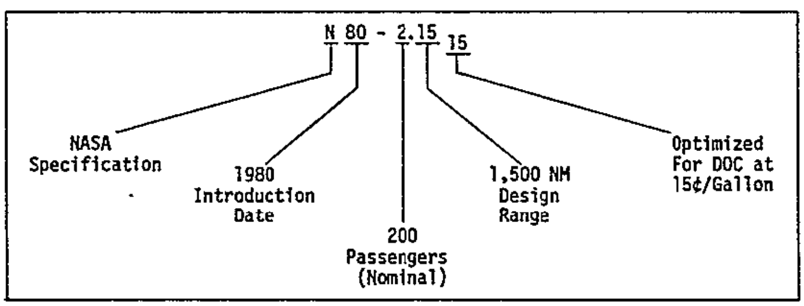


FIGURE 7. NEW NEAR-TERM AIRCRAFT DESIGNATOR CODE

4.1 N80 Aircraft Designs

Detailed interior arrangements were prepared for the N80 aircraft to assure consistent passenger conveniences with the DC-10 study baseline aircraft. Both 201 seat and 404 seat configurations were studied. Design specifications for the N80 aircraft are given in Table 13.

Advanced technologies for the N80 aircraft include supercritical wings, CF6-6 or CFM-56 type engines, thinwall composite nacelles, composite structure in floor beams, doors, nacelles, control surfaces, fairings, and wing panels, isogrid window belt structure, carbon brakes, and longitudinal stability augmentation.

Aircraft cruise Mach numbers were optimized in the range 0.70 - 0.90. Both swept and straight wing designs were considered for minimum DOC as well as minimum fuel airplanes.

TABLE 13

NEW AIRPLANE SPECIFICATIONS

NEW AIRPLANE FAMILY	N80-2.15	N80-2.30	N80-2.55	N80-4.30	N80-4.55
Cruise Mach Number	.70-.90	.70-.90	.70-.90	.70-.90	.70-.90
Engines: Number, Location	2, Wing	4, Wing	4, Wing	4, Wing	4, Wing
Type	CF6-6	CFM-56	CFM-56	CF6-6	CF6-6
Number of Crew	3	3	3	3	3
Number of Pax (10/90 Split)	201	201	201	404	404
Seats Abreast	7	7	7	9	9
Galley Location	Upper	Upper	Upper	Lower	Lower
Design Range (NM)	1,500	3,000	5,500	3,000	5,500
Maximum Takeoff Distance (Ft)	7,000	8,000	10,000	9,000	11,000
Maximum Approach Speed (Kt)	120	125	130	130	130
Initial Cruise Altitude (Ft)	31,000	31,000	31,000	31,000	31,000
Airfoil Type	SCW	SCW	SCW	SCW	SCW
Target Noise Levels	FAR 36-10	FAR 36-10	FAR 36-10	FAR 36-10	FAR 36-10

The final N80 configurations were the result of a systematic optimization study, using the Douglas Passenger Aircraft Sizing and Analysis Program (PASAP). Resulting domestic range aircraft characteristics are given in Tables 14 through 16. Characteristics of the two international range families are presented in Section 7.4.3.

TABLE 14

OPTIMUM N80-2.15 AIRCRAFT CHARACTERISTICS

2 CF6-6D Type Engines, 201 Passengers, 1,500 NM Range

		OPTIMIZATION PARAMETER			
		DOC_{15}	DOC_{30}	DOC_{60}	BLOCK FUEL
Takeoff Gross Weight	Lb	234,700	231,200	231,600	236,300
Operational Empty Weight	Lb	148,900	149,100	151,200	159,000
Cruise Mach Number		0.85	0.81	0.78	0.70
Block Time (1)	Hr	3.43	3.57	3.69	4.05
Block Fuel (1)	Lb	33,220	30,440	29,030	27,250
Critical Field Length	Ft	7,000	7,000	7,000	7,000
Approach Speed	KEAS	120	120	120	116
Thrust Per Engine Uninstalled	Lb	39,600	36,580	34,590	29,470
Direct Operating Cost (1)	¢/Seat-NM				
@ 15¢ Per Gallon		1.157	1.169	1.191	1.274
@ 30¢ Per Gallon		1.386	1.379	1.390	1.462
@ 60¢ Per Gallon		1.844	1.798	1.789	1.839
Geometry					
Aspect Ratio		7.7	9.4	10.9	15.5
Quarter Chord Sweep	Deg	35	32	28	3.2(2)
Average Thickness-To-Chord Ratio		0.148	0.143	0.140	0.128
Taper Ratio		0.30	0.30	0.30	0.30
Wing Area	Ft^2	2,267	2,197	2,130	2,135
Fuel Use @ 1,000 NM	BTU/ASNM	1,966	1,814	1,730	1,656

(1) At Design Range, 100 Percent Load Factor
(2) Straight Rear Spar

TABLE 15

OPTIMUM N80-2.30 AIRCRAFT CHARACTERISTICS

4 CFM-56 Type Engines, 201 Passengers, 3,000 NM Range

		OPTIMIZATION PARAMETER			
		DOC_{15}	DOC_{30}	DOC_{60}	BLOCK FUEL
Takeoff Gross Weight	Lb	279,800	275,700	271,500	274,300
Operational Empty Weight	Lb	156,000	157,400	157,500	164,700
Cruise Mach Number		0.85	0.82	0.78	0.70
Block Time (1)	Hr	6.52	6.74	7.05	7.77
Block Fuel (1)	Lb	69,660	65,190	61,550	58,150
Critical Field Length	Ft	6,790	6,877	7,660	8,000
Approach Speed	KEAS	125	125	125	116
Thrust Per Engine Uninstalled	Lb	20,670	18,590	16,580	13,980
Direct Operating Cost (1)	¢/Seat-NM				
@ 15¢ Per Gallon		1.187	1.205	1.237	1.335
@ 30¢ Per Gallon		1.429	1.427	1.448	1.535
@ 60¢ Per Gallon		1.908	1.879	1.872	1.937
Geometry					
Aspect Ratio		7.8	9.6	11.0	15.5
Quarter Chord Sweep	Deg	36.5	33.0	30.7	3.2(2)
Average Thickness-To-Chord Ratio		0.1418	0.137	0.136	0.130
Taper Ratio		0.30	0.30	0.30	0.30
Wing Area	Ft^2	2,286	2,215	2,150	2,250
Fuel Use @ 1,000 NM	BTU/ASNM	2,064	1,962	1,879	1,832

(1) At Design Range, 100 Percent Load Factor
(2) Straight Rear Spar

TABLE 16

OPTIMUM N80-4.30 AIRCRAFT CHARACTERISTICS

4 CF6-6D Type Engines, 404 Passengers, 3,000 NM Range

		OPTIMIZATION PARAMETER			
		DOC_{15}	DOC_{30}	DOC_{60}	BLOCK FUEL
Takeoff Gross Weight	Lb	527,400	519,100	517,200	548,200
Operational Empty Weight	Lb	301,400	304,700	309,100	345,300
Cruise Mach Number		0.85	0.82	0.79	0.70
Block Time (1)	Hr	6.52	6.78	6.96	7.77
Block Fuel (1)	Lb	121,910	111,740	106,420	102,960
Critical Field Length	Ft	9,000	9,000	9,000	9,000
Approach Speed	KEAS	123	125	125	115
Thrust Per Engine Uninstalled	Lb	35,830	32,120	29,600	27,600
Direct Operating Cost (1)	¢/Seat-NM				
@ 15¢ Per Gallon		0.843	0.846	0.857	0.959
@ 30¢ Per Gallon		1.050	1.036	1.038	1.136
@ 60¢ Per Gallon		1.464	1.416	1.400	1.489
Geometry					
Aspect Ratio		7.75	9.5	11.0	15.5
Quarter Chord Sweep	Deg	35.5	32.5	29.0	3.2(2)
Average Thickness-to-Chord Ratio		0.144	0.140	0.139	0.135
Taper Ratio		0.30	0.30	0.30	0.30
Wing Area	Ft^2	4,240	4,030	3,950	4,500
Fuel Use @ 1,000 NM	BTU/ASNM	1,740	1,611	1,542	1,533

(1) At Design Range, 100 Percent Load Factor
(2) Straight Rear Spar

4.2 Comparison of N80 Aircraft

The variation of optimum geometry and optimum cruise Mach number with fuel price is given in Figure 8 for the N80-2.30 family. The other N80 families show similar variations. The results indicate that as design fuel price increases, the importance of short block time decreases, and cruise Mach number is reduced. As cruise Mach number decreases, the optimum geometry changes (increased aspect ratio, decreased sweep and thickness) to reduce drag which results in reduced engine size and fuel consumption.

The fuel use parameters for all of the N80 aircraft at their design ranges are shown in Figure 9. The results show the effect of design fuel price on energy efficiency. The energy efficiency penalty for long range capability is also shown. As the range increases, the payload capacity must also be increased to maintain high energy efficiencies.

The N80 aircraft can save a considerable amount of fuel, relative to existing baseline aircraft in the fleet, as shown in Figure 10. Comparisons are made at one-third of the design range of the N80 airplanes. The fuel use improvements shown appear to be very large, but require some qualification because airplanes with unequal capabilities are being compared. In particular, the N80 airplanes were designed to carry only a full cabin payload plus baggage, while existing baseline aircraft were sized to carry cargo in addition to a full load of passengers and bags. Also, the design flight profiles for the N80 airplanes include cruise climb, which is more efficient than the step altitude profiles used to calculate fuel burned by the baseline airplanes.

The N80-2.15 family has a considerable edge over the DC-9-30 in seat-mile fuel economy, most of which is due to the N80-2.15 having more than twice as many seats. Also, in comparing the N80-2.15 to the DC-10-10, it must be emphasized that the relatively long-range DC-10-10 is being compared at 500 nautical miles to an aircraft family optimized for short ranges. Similarly, the N80-4.30 family seat-mile fuel economy is substantially better than the substantially smaller DC-8-61 and DC-10-10; and the design ranges of the DC-8-61 and DC-10-10 are greater than for the N80-4.30 family.

The N80-2.30 and DC-8-61 have similar passenger capacities, but different design ranges. The N80-2.30 and DC-10-10 have different capacities and design ranges. So comparisons are not on a consistent basis, but these are the closest baseline aircraft types to compare to the N80-2.30 family. By interpolating the 30 cent and 60 cent cases for the N80-2.30 in Figure 10, it appears that, at a design fuel price of 45 cents per gallon, the N80s are approximately 26% more efficient than current narrow-body aircraft and 16% more efficient than current wide-body aircraft. However, considering differences in payload-range capabilities and cruise altitude profiles, the efficiencies of the N80s would be more accurately placed at 20% better than narrow-body aircraft and 10% better than current wide-body aircraft.

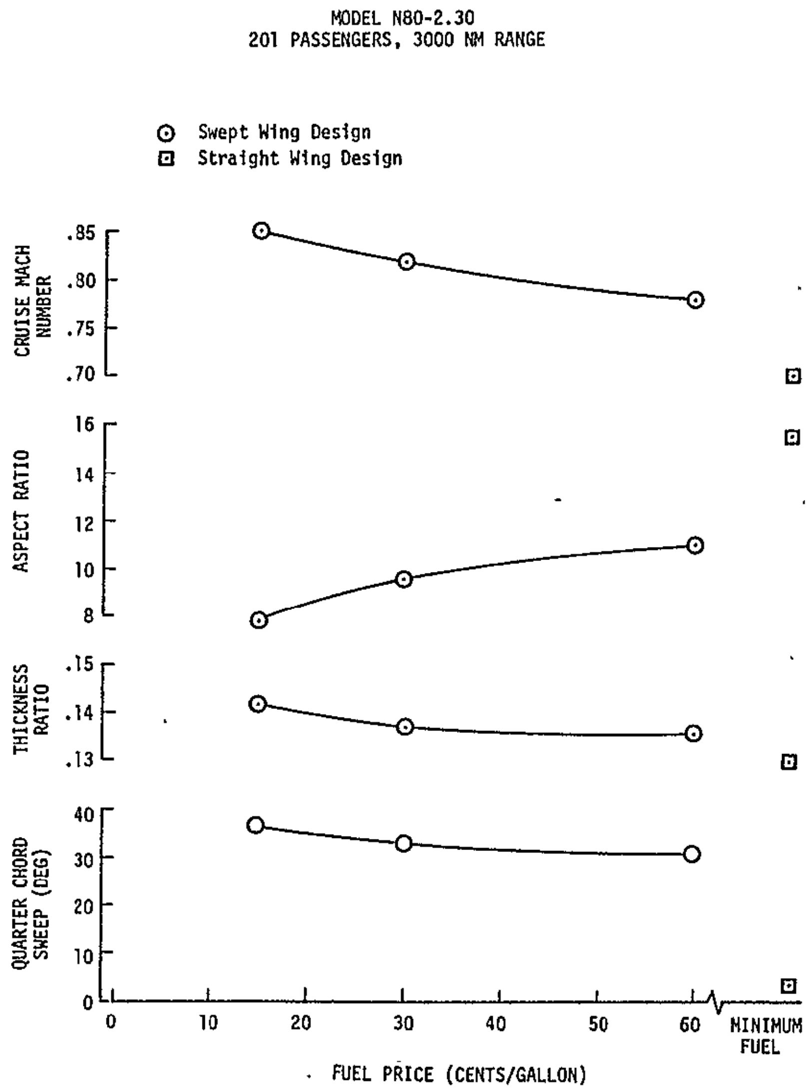


FIGURE 8. EFFECT OF FUEL PRICE ON N80-2.30 OPTIMUM AIRCRAFT GEOMETRY AND CRUISE MACH NUMBER

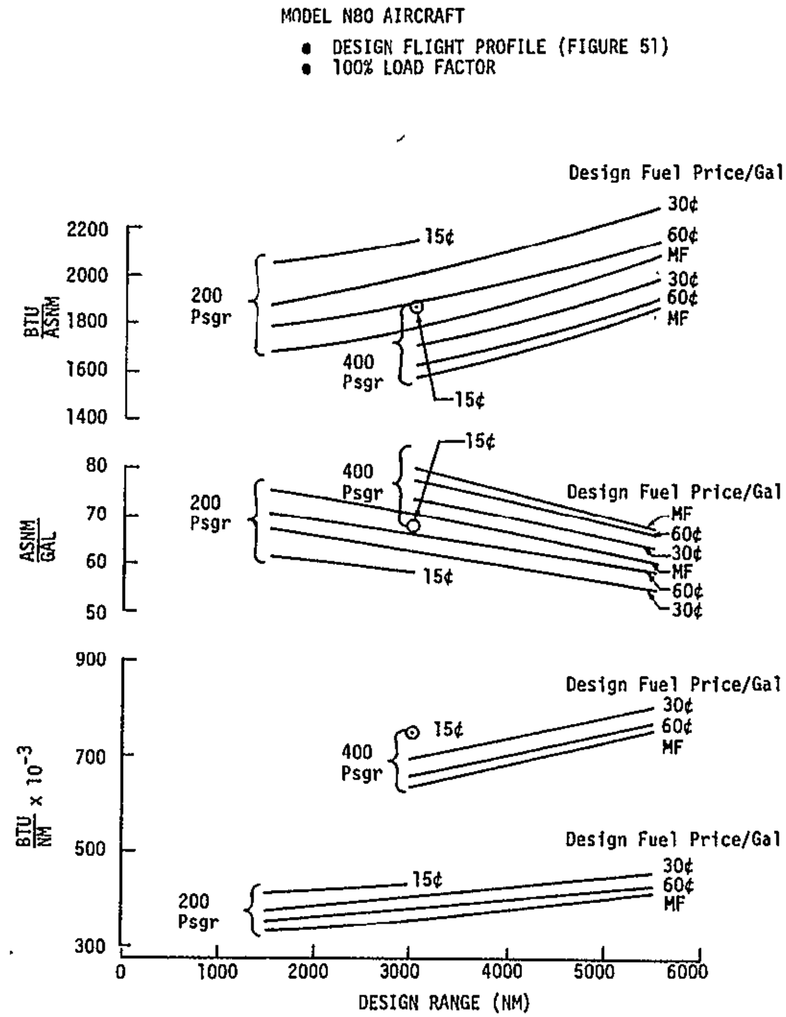


FIGURE 9. ENERGY EFFICIENCY PARAMETERS AT DESIGN RANGE FOR OPTIMUM N80 AIRCRAFT

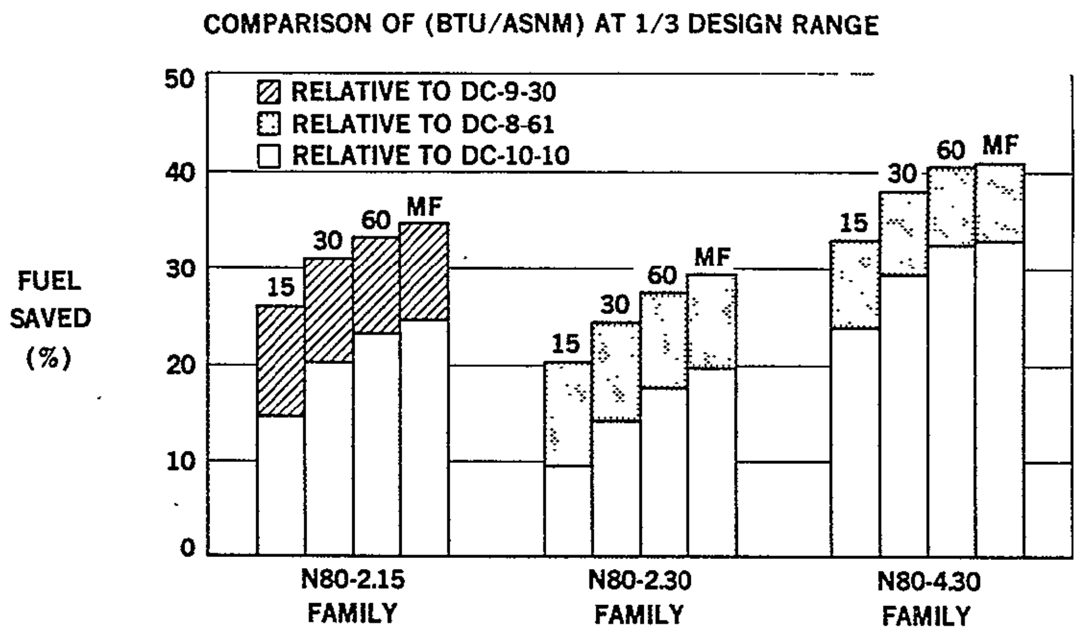


FIGURE 10. NEW NEAR-TERM AIRCRAFT FUEL SAVINGS

4.3 N80 Noise Characteristics

FAR Part 36 noise levels were estimated for the three domestic range families of N80 aircraft. Effective perceived noise level (EPNL) maps and 85, 90, and 95 EPNdB noise contours were generated for six of the aircraft configurations. The new near-term aircraft generally meet or are close to FAR 36 -10 sideline and takeoff noise levels. Approach noise levels do not meet the FAR 36 -10 goal, but improve with increasing design fuel price. Noise contour areas for the N80-2.30 family, with four CFM-56 type engines, were the lowest. The contour areas are primarily affected by payload-range capability, and are only mildly affected by the optimization parameters. Nevertheless, it is clear that energy conservative aircraft design is not in conflict with the desire for low noise.

SECTION 5.0

ECONOMIC ANALYSIS

In order to assess the economic viability of each aircraft option, consistent aircraft prices and operating costs were developed. To provide a base for comparisons, the fuel consumption and the operating costs of the baseline aircraft were compiled. Before an aircraft option was offered to the market, it was initially screened on the basis of fuel saved as well as direct and total operating costs.

5.1 Economic Groundrules

The groundrules used in the economic analyses were agreed upon by all the RECAT Study contractors and NASA. All costs and prices were in 1973 constant dollars. Direct operating costs were calculated using a modified 1967 ATA DOC formula and indirect operating costs were calculated using the 1969 Lockheed Committee IOC formula. Both formulas were calculated at 1973 cost levels.

5.2 Direct Operating Costs

Direct operating costs include the majority of aircraft-related expenses: cockpit crew, fuel, insurance, depreciation, as well as engine and airframe maintenance including maintenance burden. The study contractors and NASA agreed to use the 1967 ATA DOC method updated to 1973 cost levels to compute comparable and consistent DOC's.

All direct operating costs were computed at various stage lengths for the three NASA-specified fuel prices: 15¢, 30¢ and 60¢ per gallon. Total DOC's and the cost components were also tabulated in terms of dollars per block hour ($/HR), dollars per nautical mile ($/NM), and cents per available seat-nautical mile (¢/ASNM). Since 46 airplanes were analyzed in this study, all DOC data for the individual aircraft will be found in the Appendix of the Final Report (Volume II).

5.2.1 Effect of Fuel Price on DOC - The dramatic effect fuel price has on direct operating costs is illustrated for the baseline aircraft in Figure 11. Fuel costs represent about 25% of DOC with fuel at 15¢ per gallon, 40% at 30¢ per gallon, and 50 to 60%, more than one-half of all direct operating costs, at 60¢ per gallon. With all other DOC elements held constant, an increase in fuel price from 15¢ to 30¢ per gallon raises DOC's by about 25%. An increase from 30¢ to 60¢ per gallon raises DOC's by approximately an additional 40%.

5.2.2 Impact of Fuel Conserving Operational Procedures on DOC - The effect of fuel conserving operational procedures on direct operating costs for each of the baseline airplanes was also investigated. Two levels of improved flight operations were considered. The fuel savings the airlines could achieve right away under the present ATC system, and the reduction in fuel consumption that could be achieved under an improved air traffic control system assumed to be available in 1980.

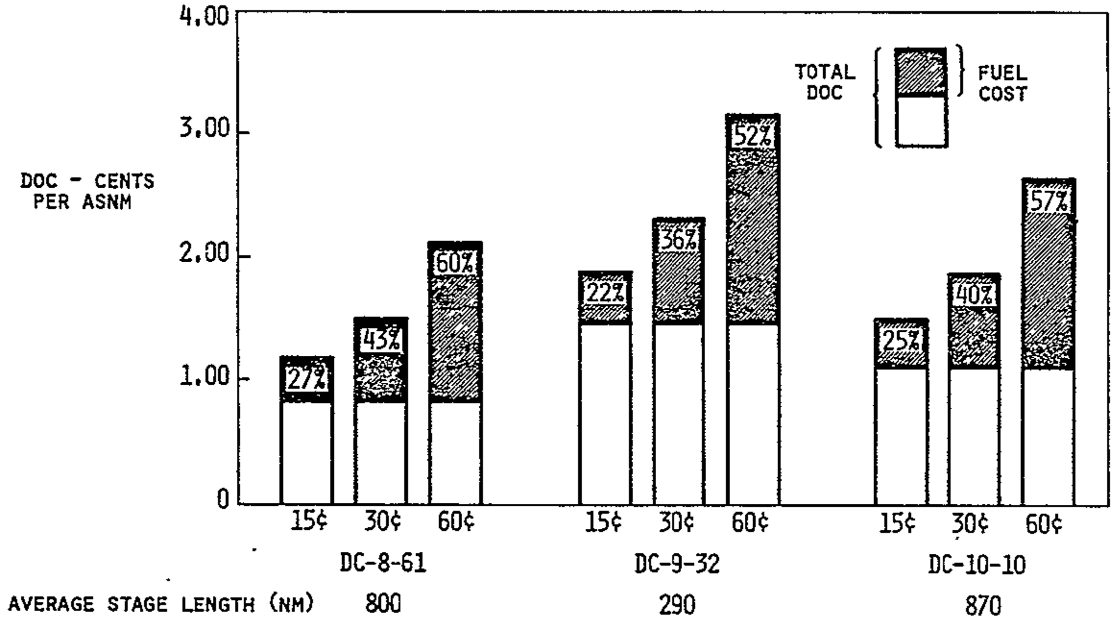


FIGURE 11. FUEL COST AS A PERCENT OF TOTAL DOC AT THREE FUEL PRICES - 15¢, 30¢, and 60¢ PER GALLON

With fuel at 30¢ per gallon, the benefits from an improved 1980 ATC environment were clearly visible. DOC's were reduced by 1.5 to 2.5% for the baseline aircraft. However, fuel savings achieved with improved flight operations under the present ATC system were not significant enough to result in DOC improvements at a fuel price of 30¢ per gallon. This was due to increased block times of 7 to 10% at the average stage length that resulted from the slowing down of the baseline airplanes to conserve fuel.

With a fuel price of 60¢ per gallon, fuel savings from operational procedures under an improved 1980 ATC system results in DOC savings of between 3.5 to 5% for the baseline airplanes. Under the present ATC system, fuel conserving procedures provided DOC savings of approximately 1% for the DC-9-30 and DC-10-10, and a little more than 1% for the DC-10-40.

Figure 12 illustrates the effects on fuel burn, block time, and DOC's under the two levels of fuel conserving flight operations for the DC-9-30 and DC-10-10. For both aircraft, under the present ATC environment, block times increase significantly while fuel savings are not as large as under the improved 1980 ATC system. Therefore, in general, it takes a fuel price of 60¢ per gallon for the present improved flight operations considered in this study to pay off economically, even though there are fuel savings.

5.3 Comparative Direct Operating Costs

5.3.1 Retrofit, Modification, and Derivative Options - The DOC's for the retrofit, modification and derivative aircraft options were compared to those of the baseline aircraft at fuel prices of 30¢ and 60¢ per gallon. Results

of these comparisons in terms of ¢/ASNM at the 1973 CAB average stage length are shown in Figures 13 and 14. As might be expected, when fuel price increases from 30¢ (Figure 13) to 60¢ per gallon (Figure 14) more aircraft options become economically attractive than with 30¢ fuel.

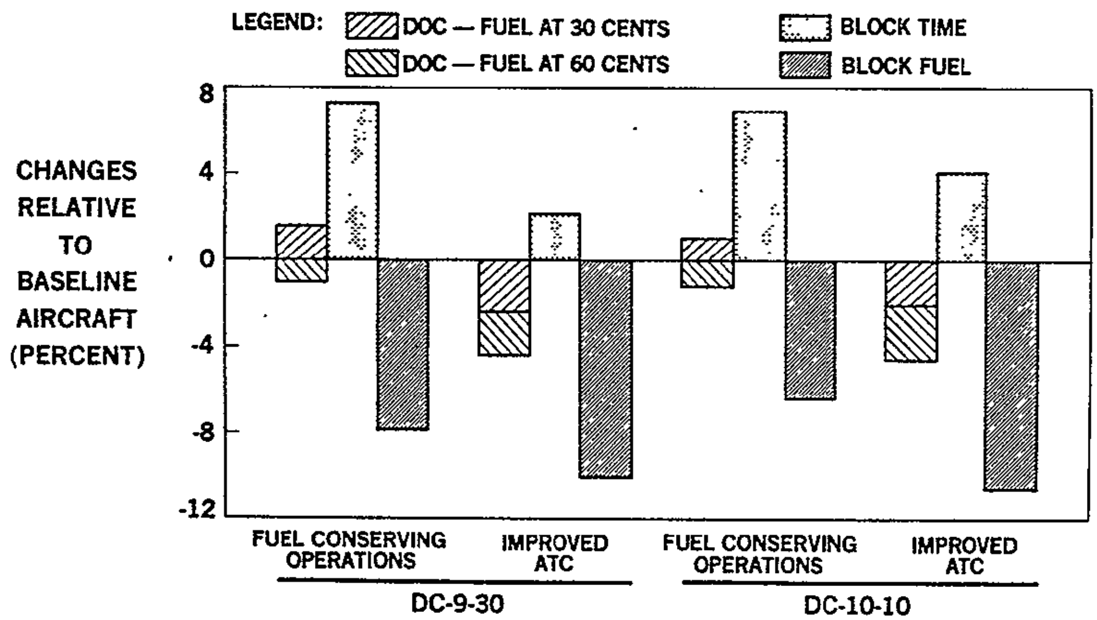


FIGURE 12. EFFECT OF OPERATIONAL CHANGES ON DOC, BLOCK FUEL AND TIME At Average Stage Length (NM)

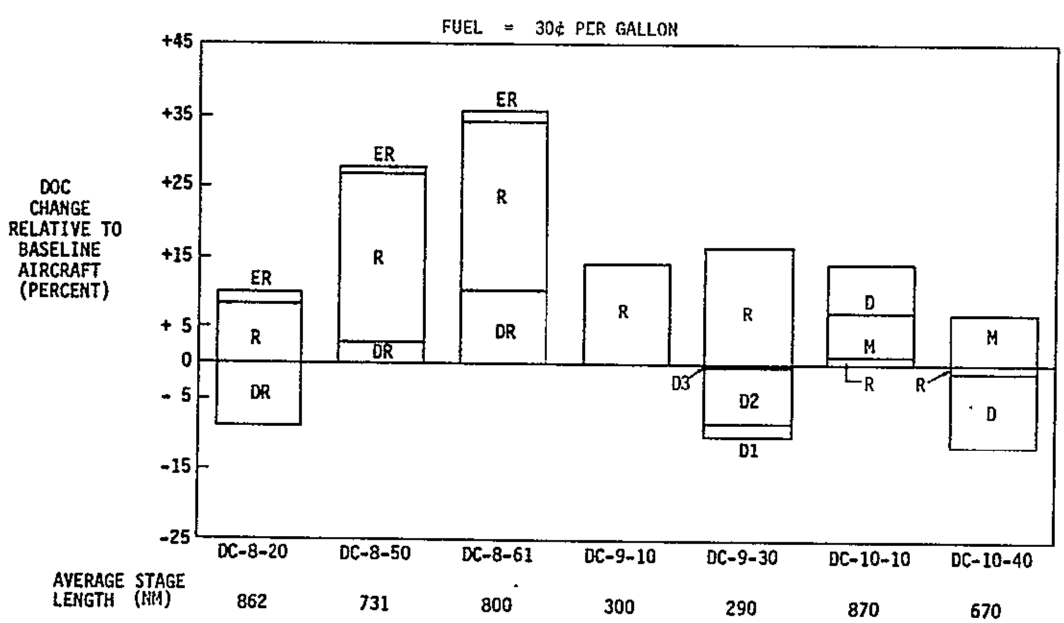


FIGURE 13. RETROFITS, MODIFICATIONS AND DERIVATIVES - DOC CHANGE (PERCENT)

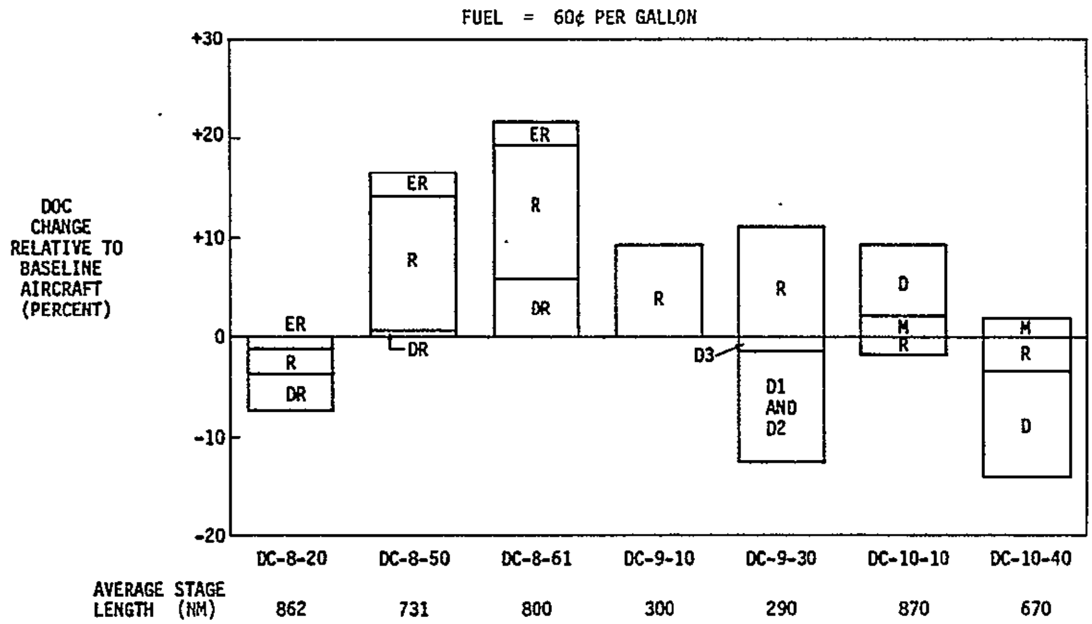


FIGURE 14. RETROFITS, MODIFICATIONS AND DERIVATIVES - DOC CHANGE (PERCENT)

DC-8 Aircraft Options - The aerodynamic retrofits on the older DC-8's offer the greatest feasibility for retrofitting. The new engine retrofits and the retrofits combining a new engine and aerodynamic improvements do not appear to be economically viable options. This is due to the cost of the new engines at $2.64 million, as well as the expense of modifying the airframe to accept the engines, approximately $2 million for each DC-8 model.

DC-9 Aircraft Options - The retrofits studied on the DC-9-10 and DC-9-30 airplanes did not offer significant fuel savings and sizeably increased DOC's at both fuel prices. On the other hand, the three DC-9-30 derivative models all provided significant fuel savings as well as a reduction in DOC's.

DC-10 Aircraft Options - The DC-10 aerodynamic retrofits do appear to be economically viable. They offer significant fuel savings, approximately 9%, with a modest improvement in DOC's with fuel at 60¢ per gallon. The DC-10 modification options do offer fuel savings but not enough to offset the resulting increase in DOC's.

Viewing the DOC's of the two DC-10 derivative options studied in terms of $/NM removes the effect of seat density biases. The DC-10-10D, the shortened DC-10, was a very viable option with a 30% improvement in fuel burned per nautical mile and a substantial reduction in DOC's over the baseline DC-10-10. On the other hand, fuel savings per nautical mile for the DC-10-40, a stretched DC-10, were not significant enough at 6% to offset the resulting large increase in DOC's per nautical mile.

5.3.2 New Near-Term (1980) Aircraft Options - DOC's for the four optimized aircraft within each of the three N80 families were compared at various stage lengths and fuel prices of 30¢ and 60¢ per gallon. The airplanes within each

family optimized for minimum direct operating costs at a specific fuel price obviously had the lowest DOC's at that fuel price. However, the DOC's for all the aircraft within a family optimized for minimum DOC's were very nearly the same.

The DOC's for the airplanes optimized for minimum fuel consumption are between 6 and 10% higher than for the airplanes optimized for DOC's at 30¢ per gallon at the maximum design ranges. When fuel is at 60¢ per gallon, the DOC's for the minimum fuel airplanes are between 3 and 6% higher than for the airplanes designed for minimum DOC's at 60¢ per gallon. This illustrates that as fuel price increases, the direct operating costs of an airplane optimized for minimum DOC's and one optimized for minimum fuel consumption approach each other. At some higher fuel price, the DOC's for both aircraft types will be equal.

Relative to Baseline Aircraft - The direct operating costs of the new near-term (1980) airplanes were compared with the DOC's of several baseline airplanes as shown in Figure 15. These comparisons in terms of ¢/ASNM were made at one third the design ranges of the N80 airplanes since the typical average stage lengths of current aircraft in domestic operations are approximately one third of their design ranges.

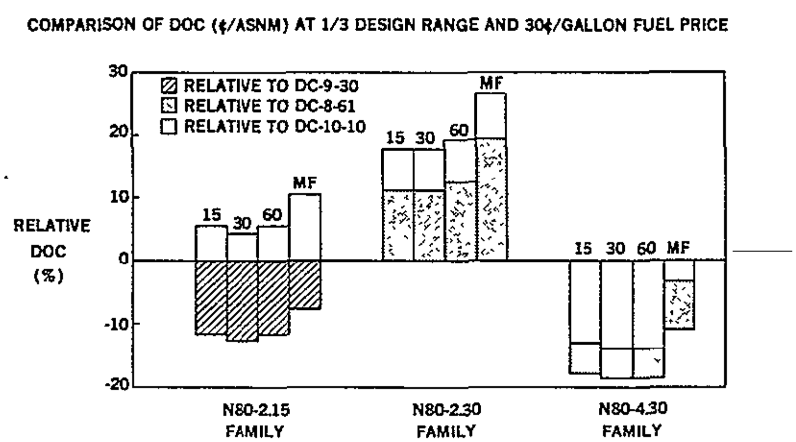


FIGURE 15. NEW NEAR-TERM AIRCRAFT FUEL SAVINGS AND DOC COMPARISON

The N80-2.15 family's DOC's are between 10 and 15% lower than those of the DC-9-30 and between 5 and 10% higher than those of the DC-10-10. However, DOC's for the N80-2.30 airplanes were considerably higher than those for the DC-8-61 (between 12 and 20% higher) and for the DC-10-10 (between 18 and 26% higher).

The N80-4.30 family's DOC's were significantly lower than those of the DC-8-61 (between 6 and 14% lower) and of the DC-10-10 (between 11 and 19% lower) primarily due to the large differences in seating capacity.

Relative to Derivative Aircraft Options - Further DOC comparisons for the N80 aircraft were made with those of the derivative aircraft options as shown in Table 17. Several conclusions are apparent from the chart.

TABLE 17

COMPARATIVE DIRECT OPERATING COSTS
FUEL = 30¢ PER GALLON

$N80-2.15_{30}$ (200 PSGRS, 1500 NM DESIGN RANGE)
At 1/3 Design Range - 500 Nautical Miles

Aircraft Type (Psgrs, Design Range)	DC-9-30 92, 1220 NM	DC-9-30D1 117, 1350 NM	DC-10-10 277, 3415 NM	DC-10-10D 199, 2900 NM
Relative DOC:				
\$/NM	1.915	1.660	.759	.936
¢/ASNM	.876	.966	1.046	.926

$N80-2.30_{30}$ (200 PSGRS, 3000 NM DESIGN RANGE)
At 1/3 Design Range - 1000 Nautical Miles

Aircraft Type (Psgrs, Design Range)	DC-8-61 203, 3250 NM	DC-10-10 277, 3415 NM	DC-10-10D 199, 2900 NM
Relative DOC:			
\$/NM	1.106	.853	1.053
¢/ASNM	1.117	1.175	1.042

$N80-4.30_{30}$ (400 PSGRS, 3000 NM DESIGN RANGE)
At 1/3 Design Range - 1000 Nautical Miles

Aircraft Type (Psgrs, Design Range)	DC-8-61 203, 3250 NM	DC-10-10 277, 3415 NM	DC-10-10D 199, 2900 NM	DC-10-40D 327,4870 NM
Relative DOC:				
\$/NM	1.615	1.245	1.537	.967
¢/ASNM	.812	.854	.757	.783

First, the $N80-2.15_{30}$ airplanes DOC's are 7% lower than those of the DC-10-10D at a stage length of 500 nautical miles. However, it should be emphasized that the relatively long-range DC-10-10D is being compared at 500 nautical miles to an aircraft optimized for operations at short stage lengths. In comparing the $N80-2.15_{30}$ to aircraft having more compatible design ranges, namely the DC-9-30 and DC-9-30D1, the $N80-2.15_{30}$ has a considerable advantage in seat-mile economy because it carries more seats.

Secondly, it appears from the chart that the $N80-2.30_{30}$ airplane is not a viable aircraft option for an airline attempting to maximize profits. This airplane's DOC's are not competitive at a 1,000 nautical mile stage length with the DOC's of any of the baseline or derivative aircraft likely to be operating in the same markets as the $N80-2.30_{30}$. This is due to the lower purchase prices of the DC-8-61 and DC-10-10D for essentially the same seating capacity, while the equivalent priced DC-10-10 offered 39% more seats than the $N80-2.30_{30}$.

Additionally, the N80-4.3030 seat-mile DOC is substantially better than those for aircraft with half the seats, the DC-8-61 and DC-10-10D as well as the baseline DC-10-10 with only 70% of the seating capacity. Also the DOC's for the N80-4.3030 airplane are 3% lower in dollars per nautical mile and almost 22% lower in ¢/ASNM than the DOC's of the DC-10-40D.

5.4 Selection of Aircraft Options

5.4.1 Direct Operating Costs - As can be seen, DOC comparisons on a consistent basis were difficult, since an aircraft with lower direct operating costs than a competitive aircraft option in terms of $/NM, often had higher DOC's in terms of ¢/ASNM or vice versa. Therefore, the relative ranking of the aircraft options with respect to DOC's alone would be inconclusive primarily because aircraft with unequal capabilities are being compared. They have widely varying design ranges as well as seating capacities. Also, it should be noted that the N80 airplanes were designed to carry only a full passenger payload plus baggage, while the baseline airplanes and the derivative options were sized to carry cargo as well. Additionally, fuel savings achieved by the N80's were based on cruise climb procedures rather than step altitude profiles. Since cruise climb is more fuel efficient than the step altitude profiles used for the baseline and derivative airplanes, fuel savings from the N80 aircraft are larger than would have been achieved with the presently more realistic step altitude profiles.

5.4.2 Market Requirements - Therefore, realistically evaluating the DOC improvement of one aircraft over another involves comparing the economic and operational performance of each aircraft in a particular market. Also an airline's route structure can determine the selection of one aircraft type over another when they are compared operationally with the airline's current fleet over its entire routing network. Consequently, all 32 selected aircraft options were allowed to prove their economic viability in the marketplace during the fleet forecasting phase of the study (Section 6.0).

5.5 Indirect Operating Costs

In contrast to the direct operating costs which are aircraft related, the majority of airline indirect operating costs are considered to be nonaircraft related. Rather these costs are viewed as airline system related. They are primarily traffic (passenger and/or cargo) dependent and are heavily influenced by management philosophy.

Since IOC's are so heavily traffic, revenue and airline related, the RECAT Study contractors and NASA agreed to use the 1969 Lockheed Committee IOC formula updated to 1973 cost levels which represented the 1973 weighted average of the CAB Form 41 data for the U.S. domestic carriers. This allowed for the computation of comparable and consistent indirect operating costs for each aircraft studied. The indirect operating costs (IOC's) were determined at various stage lengths for each airplane studied in terms of dollars per block hour ($/HR), dollars per nautical mile ($/NM) and cents per available seat-nautical mile (¢/ASNM).

5.5.1 Retrofit, Modification, and Derivative Options - The IOC's for the retrofit and modification options were virtually identical to those for the baseline airplanes, and therefore, were assumed equivalent to those of their respective baseline airplanes for this study.

Table 18 compares the IOC's of the derivative aircraft options with those of the existing baseline airplanes at various stage lengths. The IOC's did not vary significantly for similar aircraft types of approximately the same seating capacities.

TABLE 18

BASELINE AND DERIVATIVE AIRCRAFT INDIRECT OPERATING COSTS - 1973 $

(Cents Per Available Seat Nautical Mile)

Aircraft Type	Seating Capacity	Stage Length (Nautical Miles)			
		500	1,000	1,500	3,000
DC-8-20	146	2.31	1.46	-	.90
DC-8-50	146	2.35	1.49	-	.91
DC-8-61	203	2.12	1.35	-	.84
DC-9-10	70	2.16	1.39	1.14	-
DC-9-30	92	2.06	1.34	1.10	-
DC-9-30D1	117	2.01	1.32	1.09	-
DC-9-30D2	122	1.99	1.31	1.08	-
DC-9-30D3	92	2.06	1.34	1.11	-
DC-10-10	277	2.18	1.37	-	.83
DC-10-10D	199	2.23	1.41	-	.86
DC-10-40	252	2.44	1.51	-	.89
DC-10-40D	327	2.19	1.38	-	.84

5.5.2 New Near-Term (1980) Aircraft Options - The IOC's for the various models within each family optimized for minimum direct operating costs were virtually the same since there was very little variation in the block times for the airplanes and the seating capacities were identical. However, the IOC's for the minimum fuel consumption aircraft within each family were between 4.5-6% higher than for the airplanes designed for minimum direct operating costs at the maximum design ranges. This was due primarily to the significant increases in block times for the minimum fuel airplanes.

5.6 Total Operating Costs

Increases in DOC's due to higher fuel prices caused the TOC's to rise similarly, while the impact of IOC's on total operating costs was reduced. Therefore, the addition of the indirect operating costs to the direct operating costs did not alter the economic selection of the aircraft options.

Each of the baseline airplanes and aircraft options were offered to the market using the fleet forecasting model discussed in Section 6.0. Since an economic selection of one aircraft type over another was not always possible due to differing seating capacities as well as design ranges, the airplanes were selected by the model on its ability to best serve each market as well as maximize system profit. Economic tradeoffs between aircraft in the fleet forecasting model were made on the basis of total operating costs.

SECTION 6.0

U.S. DOMESTIC MARKET ANALYSIS

The first objective of the market study was to develop a flexible and realistic demand projection model representative of the markets served by the U.S. domestic scheduled airlines for the study period 1973-1990. To accomplish this task a route network and baseline operating scenario were defined, and the traffic demand over this study network was then forecast.

The second and primary objective was to select the most promising modification, derivative or all-new aircraft options in terms of their potential impact on the fuel savings and economic viability of the U.S. domestic fleet, and then to project the U.S. aircraft market for the selected options. In carrying out this task, alternative operating scenarios were established to screen the aircraft options against the projected market requirements. The results of these alternative fleet forecasts were then compared both economically and operationally. Criteria used in comparing viability included operating costs, potential airline profit, passenger demand satisfied, fuel saved, as well as the forecasted fleet size and mix.

6.1 Demand Projection Model

6.1.1 Study Market - DC-Jet Route Network

The route network developed considered only the scheduled services operated with existing Douglas jet equipment by the U.S. trunk and local service carriers within the continental United States. NASA specified 1973 as the initial study year in order to provide a pre-energy crisis reference for the fleet analysis discussed in Section 6.2. The markets served and the daily city-pair operational statistics including departures, available seat-miles, and aircraft types (DC-8, DC-9, DC-10) were determined from the August 1973 official Airline Guide. Since both the DC-10 and L-1011 had not been in service long in 1973 and the number of these aircraft operating in the U.S. domestic system was so small, the L-1011 markets were combined with those of the DC-10. August was selected because it represents the peak month of the year for passenger travel in terms of determining equipment requirements.

For consistency, the available seat-miles were adjusted by aircraft type to reflect the technical groundrule of a 10/90 split between first class and coach for all seating configurations. Using the CAB's Seasonally Adjusted Data Report for the U.S. Trunks and Pan American, it was determined that the August ASM's represented 9.3 percent of the annual 1973 available seat-miles. Therefore, applying this percentage to the total August ASM's, the DC-Jet network generated 95.1 billion ASM's in 1973.

6.1.2 Study Market vs. Total U.S. Domestic Market

The revenue passenger-miles generated by the DC-Jet network represented 34 percent, 42.8 billion, of the U.S. domestic (50 state) trunk and local service carrier's RPM's, 126 billion in 1973. As shown in Figure 16, the traffic level distribution with stage length for the study market versus the actual U.S. domestic market were virtually the same, validating use of the smaller study market.

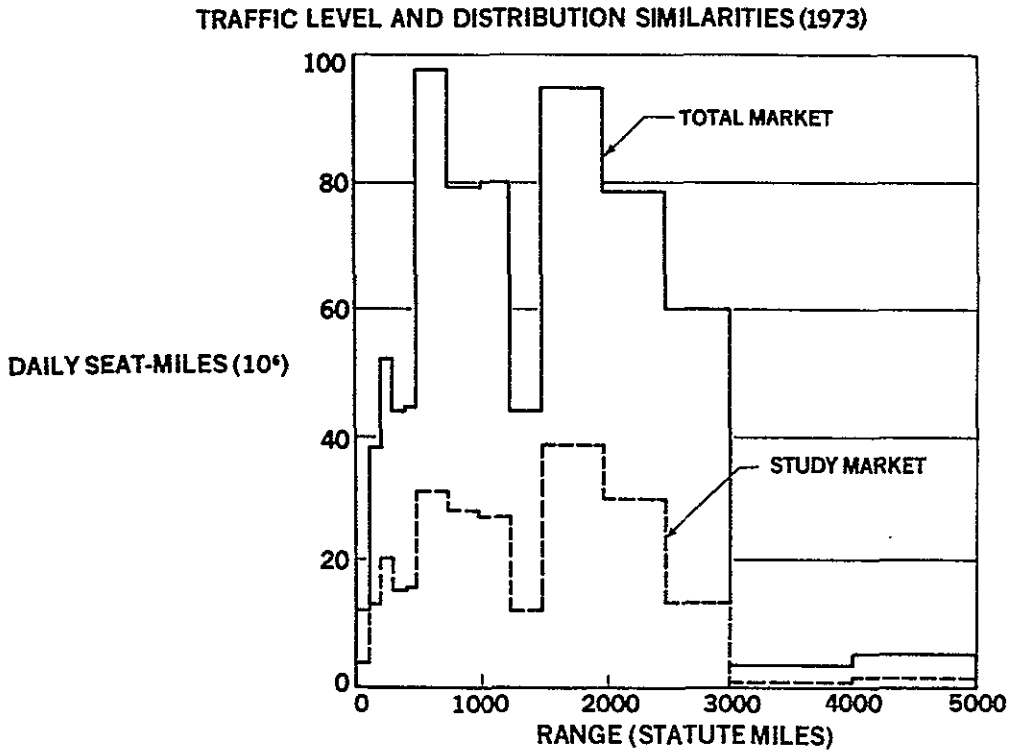


FIGURE 16. SELECTED STUDY MARKET VS. TOTAL DOMESTIC MARKET

6.1.3 Baseline Traffic Forecast (1973-1990)

From the base year 1973, passenger demand (RPM's) was projected to 1990 using the growth rates agreed upon by the RECAT Study contractors. Revenue passenger-miles were forecasted to grow at an average annual rate of

- 4.7% from 1973-1980
- 4.3% from 1981-1985
- 3.7% from 1986-1990

As shown in Figure 17, RPM's performed on the DC-Jet network double over the forecast period from 42.8 billion in 1973 to 87.3 billion in 1990. Extrapolating from the study market, the U.S. domestic system RPM's would be expected to grow from approximately 126 billion in 1973 to 257 billion in 1990 using the same annual growth rates.

6.1.4 Available Seat-Mile Potential

The actual available seat-miles generated varied under each operating scenario and was an output of the fleet forecasted for that scenario. When aircraft were added into the fleets during the study period, they were selected on the basis of their availability at a particular time, their ability to properly serve the available passenger demand, as well as their fuel and operating cost characteristics.

YEAR	AVG. ANNUAL GROWTH RATE (%)
1973-1980	4.7
1981-1985	4.3
1986-1990	3.7

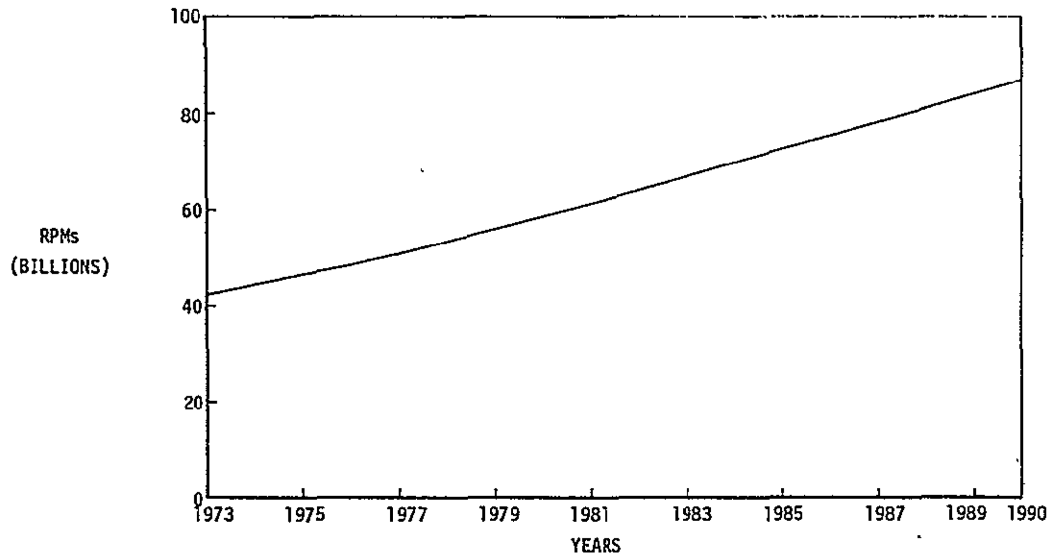


FIGURE 17. DC-JET REVENUE PASSENGER-MILE FORECAST (1973-1990)

6.2 Selection of Aircraft Options Through Alternative Fleet Forecasts

6.2.1 Study Approach

Figure 18 outlines the approach taken in selecting the most promising fuel conserving aircraft options. The alternative fleet forecasts for the study period 1973-1990 were determined using the Performance Evaluation Technique (G8BD), an existing Douglas computer program. With this method the operational and economic performances of the existing, modified, derivative, and new near-term (N80) aircraft options were measured in simulated airline operational scenarios. Inputs to the program included the passenger demand forecast discussed in Section 6.1.3, the baseline operational environment of the U.S. domestic airlines, the various alternative operating scenarios, as well as the different offerings of competitive aircraft options.

The selected aircraft options were grouped into realistic combinations of aircraft offerings for each operational scenario. The 32 selected options competed not only among themselves, but also against the baseline existing aircraft. The program selected from each offering of competitive options that fleet-mix which best satisfied the traffic demand and also met the evaluation criterion of maximizing airline profits over the forecast period. Operational conditions affecting the fleet-mix selection, including fuel availability and price, hub constraints, load factor variations, aircraft availability, and aircraft operating procedures were considered by the program along with the alternative aircraft offerings.

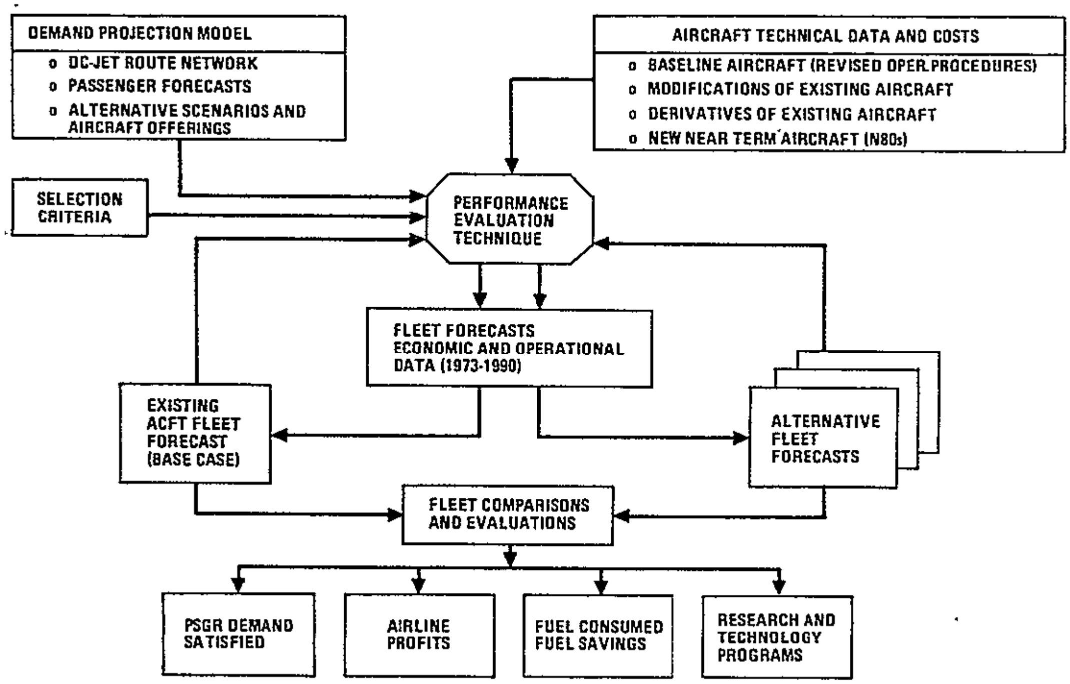


FIGURE 18. STUDY APPROACH - USE OF PERFORMANCE EVALUATION TECHNIQUE

6.2.2 Operating Profit

In order to select those fuel conserving aircraft options that maximized the fleet's operational and economic performance, the operating profit for each alternative fleet forecast was determined. Operating profit was defined as the total operating revenue from scheduled passenger and cargo services less the total operating costs.

The passenger revenue generated by a particular fleet of aircraft over the forecast period 1973-1990 was based upon the 1974 CAB Phase IX Fare Levels. This fare structure was adjusted by United Airlines to provide yield in cents per revenue passenger-mile in 1973 dollars. Revenue provided by cargo operations was based upon an estimate of the relationship between cargo revenue and passenger revenue. This relationship, also provided by United Airlines, estimated cargo revenue at 3% of the total passenger revenue.

6.2.3 Study Scenarios

Thirty-five alternative operating scenarios were developed, and each scenario was offered against the forecasted baseline 1973-1990 passenger demand or a modification of this demand. When passenger demand was modified, it was either increased or decreased by 10% from the baseline forecast. The scenarios investigated were broken down into two groups.

- 8 operating scenarios with baseline aircraft only
  - with and without hub constraints
  - with and without fuel conserving operational procedures

- 27 operating scenarios to select the most promising aircraft options
    - modification options including retrofits
    - derivative aircraft
    - new near-term (N80) airplanes

Table 19 describes each of the thirty-five operating scenarios studied in terms of its operational constraints and its offering of competitive aircraft options.

6.2.4 Baseline Operating Scenarios

The eight baseline scenarios investigated the impact of changes in operational constraints without any accompanying changes in the aircraft types offered. Only the existing Douglas airplanes in production (DC-9-30, DC-10-10, and DC-10-40) were assumed available to meet the subsequent demand. The operational conditions that were varied from scenario to scenario are underlined and the number of cases examined under each condition is given in parenthesis.

- Baseline pre-energy crisis scenario with <u>fuel price</u> at <u>15¢</u> per gallon (1)
- Baseline scenario with <u>fuel price</u> at <u>30¢</u> and <u>60¢</u> per gallon (2)
- Baseline scenario with <u>hub constraints</u> (maximum frequency limitations) - fuel at 30¢ and 60¢ per gallon (2)
- Baseline scenario with <u>allocated fuel</u> at 1973 levels - fuel at 30¢ per gallon (1)
- Implementation of <u>fuel conserving flight operations</u> with and without ATC improvements - fuel at 60¢ per gallon (2)

Except for the baseline pre-energy crisis scenario, all scenarios were analyzed at fuel prices of either 30¢ or 60¢ per gallon. The RECAT Study contractors assumed that a fuel price of 30¢ per gallon in constant 1973 dollars represented a realistic average price during the study years. A higher fuel price of 60¢ per gallon in constant 1973 dollars was used to reflect an average upper limit on fuel price over the forecast period.

Pre-Energy Crisis Scenario - The first baseline scenario reflected the actual 1973 operating environment for the domestic trunks and local service carriers. Fuel price was held constant at 15¢ per gallon and the availability of fuel was unlimited over the period. Other assumptions in this scenario included pre-energy crisis aircraft operating procedures, 1973 frequencies as a minimum, a target load factor of 58% by 1980, and fares in 1973 dollars.

The baseline revenue passenger-mile demand was used for this scenario. Also all subsequent aircraft demand was to be met by the Douglas jet equipment types on hand in 1973 and new units of those types in production after 1973 (DC-9-30, DC-10-10, DC-10-40). Although this baseline scenario is academic now, due to higher fuel prices and anticipated fuel shortages, it does represent a realistic scenario for the study period assuming there was no energy crisis. This scenario will also provide the maximum upper limit on aircraft fuel demand by the U.S. domestic carriers from 1973 to 1990.

TABLE 19

DEVELOPMENT OF FLEET FORECASTS - RUN SCHEDULE

OBJECTIVE - MAXIMIZE AIRLINE PROFIT

RUN NO.	TRAFFIC DEMAND		FLEET INVENTORY OPTIONS				AIRCRAFT INTRODUCTION DATES		AIRCRAFT OPERATING PROCEDURES		LEVEL OF SERVICE		LOAD FACTOR		FUEL AVAILABILITY		FUEL PRICE		FARES		SCENARIO DESCRIPTION
	BASE CASE	OTHER	EXIST. A/C	EXIST. MODS[1]	DERIV. A/C[2]	NEW NEAR TERM	DERIV. A/C	NEW NEAR TERM	CURRENT	FUEL CONSER.	MIN. TRIPS	MAX. TRIPS	1973 LEVEL	Δ L.F.	UNCON-STRAINED	1973 ALLOT-MENT	15¢	INC. PRICE	1973 FARES	OTHER	
1	X		X						X		X		X		X		X		X		15¢
2	X		X						X		X		X		X			30¢	X		Baseline @ 3 fuel prices 30¢
3	X		X						X		X		X		X			60¢	X		60¢
4	X		X						X		X	X	X		X			30¢	X		Hub constraints 30¢
5	X		X						X		X	X	X		X			60¢	X		60¢
6	X		X							Impr. Opers	X	X	X		X			60¢	X		Impr. Flt. Opers. - 1973 @ 60¢
7	X		X							Impr. ATC	X	X	X		X			60¢	X		Impr. Flt. Opers. plus 1980 Impr. ATC @ 60¢
8	X		X						X		X	X	X			X		30¢	X		Baseline @ 30¢ + fuel constraints
9	X		X	X					X		X	X	X			X		30¢	X		
10	X		X	X					X		X	X	X			X		30¢	X		Screening of retrofit options + fuel constraints @ 30¢
11	X		X	X					X		X	X	X			X		30¢	X		
12	X		X	S					X		X	X	X			X		30¢	X		Selected retrofit fleet + fuel constraints @ 30¢
13	X		X	S					X		X	X	X		X			30¢	X		Selected retrofit fleet without fuel constraints @ 30¢
14	X		X	S	X				X		X	X	X			X		30¢	X		Screening of derivative options + fuel constraints @ 30¢
15	X		X	S	S		X		X		X	X	X			X		30¢	X		Selected derivative fleet + fuel constraints @ 30¢
16	X		X	S	X				X		X	X	X		X			30¢	X		Screening of derivative options without fuel constraints @ 30¢
17	X		X	S	S		X		X		X	X	X		X			30¢	X		Selected derivative fleet without fuel constraints @ 30¢

S = SELECTED AIRCRAFT OPTIONS

1 - EXISTING MODS = RETROFITS

2 - IN-PRODUCTION MODS SCREENED WITH DERIVATIVE OPTIONS

TABLE 19 (CONTINUED)

DEVELOPMENT OF FLEET FORECASTS - RUN SCHEDULE

OBJECTIVE - MAXIMIZE AIRLINE PROFIT

RUN NO.	TRAFFIC DEMAND		FLEET INVENTORY OPTIONS				AIRCRAFT INTRODUCTION DATES		AIRCRAFT OPERATING PROCEDURES		LEVEL OF SERVICE		LOAD FACTOR		FUEL AVAILABILITY		FUEL PRICE		FARES		SCENARIO DESCRIPTION
	BASE CASE	OTHER	EXIST. A/C	EXIST. MODS[1]	DERIV. A/C[2]	NEW NEAR TERM	DERIV. A/C	NEW NEAR TERM	CURRENT	FUEL CONSER.	MIN. TRIPS	MAX. TRIPS	1973 LEVEL	Δ L.F.	UNCON-STRAINED	1973 ALLOT-MENT	15¢	INC. PRICE	1973 FARES	OTHER	
18	X		X	S	S	X			X		X	X	X			X		30¢	X		Screening of N80 options + fuel constraints @ 30¢ and 60¢
19	X		X	S	S	X			X		X	X	X			X		60¢	X		
20		-10%	X	S	S	S		X	X		X	X		Lower 55%		X		30¢	X	X	
21	X		X	S	S	S		X	X		X	X	X			X		30¢	X		
22		+10%	X	S	S	S		X	X		X	X		Higher 70%		X		30¢	X	X	Selected N80s fleets + fuel constraints @ 30¢ and 60¢
23		-10%	X	S	S	S		X	X		X	X		Lower 55%		X		60¢	X	X	
24	X		X	S	S	S		X	X		X	X	X			X		60¢	X		
25		+10%	X	S	S	S		X	X		X	X		Higher 70%		X		60¢	X	X	
26	X		X	S	S	X			X		X	X	X		X			30¢	X		Screening of N80 options without fuel constraints @ 30¢ and 60¢
27	X		X	S	S	X			X		X	X	X		X			60¢	X		
28		-10%	X	S	S	S		X	X		X	X		Lower 55%	X			30¢	X	X	
29	X		X	S	S	S		X	X		X	X	X		X			30¢	X		
30		+10%	X	S	S	S		X	X		X	X		Higher 70%	X			30¢	X	X	Selected N80 fleets without fuel constraints @ 30¢ and 60¢
31		-10%	X	S	S	S		X	X		X	X		Lower 55%	X			60¢	X	X	
32	X		X	S	S	S		X	X		X	X	X		X			60¢	X		
33		+10%	X	S	S	S		X	X		X	X		Higher 70%	X			60¢	X	X	
34	X		X	S	S	S		X	X		X	X		55%	X			30¢	X		Load factor variations with selected N80 fleet - no fuel constraints @ 30¢
35	X		X	S	S	S		X	X		X	X		70%	X			30¢	X		

Fuel Conserving Flight Operations - These operational procedures were assessed at two levels - those that could be implemented without a significant change in the present Air Traffic Control (ATC) System, and those that would require significant ATC changes. The first scenario represented the most fuel conserving level possible in today's ATC system. In addition to the first level of fuel conserving flight operations, the second scenario also assumed an improved ATC system operational in 1980. No attempt was made to assess the cost of implementing these improvements to the air traffic control system since this was outside the scope of the study. Instead, assumptions were made by the contractors and NASA as to the possible capabilities of the system in 1980.

6.2.5 Scenario Reference Cases

To add airline realism to the study, current and future frequency limitations at the hub airports were predicted by UAL and UTRC. Once these hub constraints were implemented into the alternative baseline scenarios, they were retained for all the improved flight operations scenarios as well as for all the twenty-seven alternative aircraft option scenarios. The baseline hub constraint scenarios with fuel at 30¢ and 60¢ per gallon were chosen as the primary reference cases against which the twenty-seven alternative scenarios were quantitatively compared because they more accurately represented the real airline environment of major airport saturation anticipated during the study period.

In order to effectively compare the results of each fleet forecast with those for the hub-constrained 30¢ and 60¢ scenarios, it was necessary to compare the fuel consumption and profit generation in terms of passenger volume. This type of efficiency comparison will continue throughout the study since the RPM's which were performed for each operating scenario were different. Therefore, fuel burns of the fleet forecasts were compared on the basis of pounds of fuel per RPM, and profit was compared on the basis of dollars of profit per RPM.

6.2.6 Summary of Fleet Forecast Results for the Baseline Operating Scenarios

Table 20 summarizes the results from the fleet forecasts for each of the eight baseline operating scenarios. The revenue passenger-miles and the required aircraft units are given for each scenario. Fuel savings are shown for the fuel allocated and fuel conserving operational scenarios relative to the study reference cases.

Under a 1980 improved ATC operating scenario, profit over the forecast period improved by almost 13% and fuel savings increased by 7.5% relative to the baseline reference case. Fuel savings for this scenario during the period that the improved ATC was operational, from 1980-1990, were over 10% relative to the reference case while generating almost an equivalent number of RPM's. Therefore, an improved ATC system that could achieve significant reductions in flight delays does appear to be a worthwhile goal in terms of fuel conservation. However, the benefits of these potential fuel savings would have to be evaluated against the cost of improving the system.

6.2.7 Alternative Aircraft Option Scenarios

Twenty-seven additional operating scenarios were used to select the most promising fuel conserving aircraft options. Each scenario included changes

TABLE 20

COMPARATIVE FLEET FORECAST RESULTS

BASELINE SCENARIOS	RPM'S (Billions)		ANNUAL FLEET SIZE (Number of Airplanes)				FUEL SAVINGS/RPM (Percent)	
	1973-1990	1980-1990	1973	1980	1985	1990	1973-1990	1980-1990
15¢ (Pre-Energy Crisis)	1144.222	799.627	559	600	675	801	—	—
30¢/Gallon Fuel	1144.222	799.627	559	600	674	783	—	—
60¢/Gallon Fuel	1144.222	799.627	559	600	670	785	—	—
Hub-Constrained @ 30¢	1105.469	763.816	559	594	647	718	—	—
Hub-Constrained @ 60¢	1103.723	762.065	559	594	645	717	—	—
Fuel Allocated @ 30¢	940.371	605.222	559	559	560	559	-2.9	6.0
Fuel Consv. Flt. Opers. (1973) @ 60¢	1102.295	761.142	559	629	684	757	4.9	6.3
Impr. ATC (1980) @ 60¢	1102.478	761.866	559	608	661	730	7.5	10.1

to the operational conditions including changes in fuel availability and price, RPM demand, and goal load factor, as well as an appropriate set of aircraft offerings from which the best fleet-mix was selected. The effect of these changes on both fuel savings and fleet requirements were assessed.

In these scenarios, subsequent aircraft demand was not limited to the existing 1973 Douglas airplane types. Additional aircraft requirements were also met by the thirty-two fuel conserving options under study. The introduction dates of the options were time-phased to represent the order in which they would become available in the marketplace.

The retrofit options, (modifications to the existing Douglas airplanes in the fleet), were screened first against the seven baseline aircraft. Next the modification options, (existing airplane types modified in-production), and the derivative aircraft were screened against both the baseline airplanes and the selected retrofit options. Finally, the new near-term 1980 technology aircraft were screened against the baseline airplanes as well as the selected retrofit, modification and derivative options.

The twenty-seven alternative operating scenarios that were studied are outlined by three general sets of aircraft offerings in Table 21. The operational constraints that were varied in the scenarios are listed, and the number of cases examined under each condition are given in parentheses.

Scenario Reference Cases - Results and fuel savings of the fleet forecasts developed from the twenty-seven alternative operating scenarios were measured against the results of the primary reference cases for this study, the baseline hub-constrained scenarios with fuel at 30¢ and 60¢ per gallon.

TABLE 21

TWENTY-SEVEN ALTERNATIVE OPERATING SCENARIOS

- Implementation of the retrofit options with fuel at 30¢ per gallon
  - Total (both drag reduction and engines) retrofits screened - fuel constrained environment only (1)
  - Drag reduction retrofits screened - fuel constrained environment only (1)
  - Engine retrofits screened - fuel constrained environment only (1)
  - Initially selected retrofits - both fuel environments (2)
- Implementation of selected retrofits with modification and derivative options - fuel at 30¢ per gallon, both fuel environments.
  - Initially selected retrofits screened with modifications and derivatives (2)
  - Selected modifications and derivatives (2)
- Implementation of selected mod options including retrofits and selected derivatives, with new near-term aircraft - fuel prices of 30¢ and 60¢ per gallon, both fuel environments.
  - Selected mod options, and derivatives screened with new near-term aircraft (4)
  - Selected mod options, derivatives, and new near-term aircraft (4)
  - Investigated the effect of varying the baseline traffic demand (8)
    - o + 10% RPM demand
    - o - 10% RPM demand
  - Analyzed the impact of load factor - without fuel constraints at a fuel price of 30¢ per gallon (2)
    - o 55% goal load factor
    - o 70% goal load factor

6.3 Summary of Results and Conclusions

6.3.1 Revenue Passenger-Miles - The RPM's flown from 1973-1990 over the study network varied under each operating scenario, because with hub constraints, the maximum number of passengers carried was dependent on the selected aircraft capacities. The RPM's for those scenarios in which only the selected aircraft options were available are shown in Table 22. Upon implementation of the hub constraints, no scenario in either fuel environment carried all the forecasted RPM demand.

In an unlimited and limited fuel environment with hub constraints, the baseline fleet performed 96.5% and 82% respectively of the total forecasted RPM demand during 1973-1990. However, when the derivative and N80 aircraft options were added into the fleets, 97-98% of the RPM's were performed in the unconstrained fuel scenarios, while the RPM's which were carried in the fuel constrained scenarios during the study period increased to 87-89%. With fuel constraints, the operating scenarios satisfied only 71-75% of the demand in 1990, while in the unconstrained fuel scenarios, only 5% of the RPM's were not carried in 1990. The revenue passenger-miles generated over the DC-Jet route network under each fuel environment were then projected to the total U.S. domestic system as shown in Table 23.

TABLE 22

COMPARATIVE FLEET FORECAST RESULTS FOR SELECTED AIRCRAFT OPTIONS

STUDY SCENARIOS	RPM'S (Billions)		ANNUAL FLEET SIZE (Number of Airplanes)				FUEL SAVINGS (Percent)	
	1973-1990	1980-1990	1973	1980	1985	1990	1973-1990	1980-1990
BASELINE SCENARIOS								
Hub-Constrained @ 30¢	1105.469	763.816	559	594	647	718	-	-
Hub-Constrained @ 60¢	1103.723	762.065	559	594	645	717	-	-
AIRCRAFT OPTION SCENARIOS								
Constrained Fuel								
Retrofits @ 30¢	988.499	652.357	559	566	577	580	3.2	5.4
Mods + Derivs. @ 30¢	990.821	657.690	559	575	590	594	4.5	7.3
Mods & Derivs. + N80s @ 30¢	1015.761	682.630	559	572	579	581	8.1	12.5
Mods & Derivs. + N80s @ 60¢	1002.882	669.889	559	550	568	573	8.1	12.6
Unlimited Fuel								
Retrofits @ 30¢	1105.091	764.051	559	590	643	714	1.4	2.0
Mods + Derivs @ 30¢	1115.868	774.263	559	598	642	727	4.7	7.0
Mods & Derivs. + N80s @ 30¢	1116.354	774.749	559	592	637	716	6.8	10.2
Mods & Derivs. + N80s @ 60¢	1109.657	769.789	559	589	634	710	7.6	11.1

TABLE 23

PROJECTION OF U.S. DOMESTIC SYSTEM RPM's (1973-1990)

	DC-Jet Network	U.S. Domestic System
Without Fuel Constraints	1105 - 1144 Billion	Approx. 3300 Billion
With Fuel Constraints	990 - 1015 Billion	Approx. 2950 Billion

Traffic Demand Variations - From this preliminary analysis, it was apparent that fuel savings of between 3-4% per RPM could be realized with a 10% increase in RPM demand over the forecast period. These savings were virtually the same under both fuel environments and both fuel prices of 30¢ and 60¢ per gallon. On the other hand, when RPM demand was reduced by 10%, the fuel burned per RPM by the forecasted fleets over the same period increased by 3-4% regardless of fuel environment or fuel price. With increased RPM demand, larger more fuel efficient aircraft were able to satisfy the minimum frequency requirements that had previously precluded their profitability on certain low traffic routes. Conversely, with decreased RPM demand, the aircraft previously selected as satisfactory could no longer profitably meet the minimum frequency levels and were replaced by smaller less fuel efficient types.

Fare Variations - Also from this analysis, it appears that in both fuel environments and a fuel price of 30¢ per gallon, a 10% increase in RPM demand would allow a 5% reduction in fares to achieve the same profit per RPM as the N80 scenarios with the baseline traffic demand. A 10% decrease in RPM's would require a 5% increase in fares to achieve the same profit level as the baseline N80 cases.

With a fuel price of 60¢ per gallon in either fuel environment, a 10% increase in traffic demand would allow approximately a 12-13% decrease in fare levels while a decrease in RPM demand of 10% would require a 15-20% increase in fares to achieve the same profit per RPM as the baseline N80 cases.

6.3.2 Fleet Sizes - The fleet sizes predicted for 1990 on the DC-Jet network were obviously dependent on the fuel environment. With the implementation of fuel constraints, the fleet size required was considerably smaller due to the lack of ability to perform all the RPM demand within the allocated fuel levels.

The actual fleet sizes required by operating scenario and fuel environment from 1973-1990 are given in Table 22. The average fleet sizes needed in 1990 for the DC-Jet network with and without fuel constraints are shown in Table 24. Using these average fleet sizes, the number of aircraft needed for the total U.S. domestic system in 1990 were estimated and are also given in the table. The estimated fleet size for the U.S. domestic system with no fuel constraints correlates well with other recent studies predicting fleet sizes of approximately 2100 airplanes in 1990.

Table 24

1990 FLEET SIZES

	DC-Jet Network	U.S. Domestic System
Without Fuel Constraints	700 - 725	2050 - 2150
With Fuel Constraints	575 - 600	1700 - 1800

6.3.3 Selected Aircraft Options - The types and numbers of each aircraft required in each scenario varied, but certain aircraft options were selected in sufficient quantity by the market in almost every scenario, and these are listed in Table 25. Out of the 32 aircraft options studied, 10 were selected as the most promising for fuel conservation as well as being economically and operationally viable under the two fuel environments examined.

The potential U.S. market requirement for each selected aircraft option was also projected and is given in Table 26. For the selected retrofit aircraft options, the potential program size was equal to the total numbers of existing aircraft of that type available for retrofitting in the U.S. airline fleets.

TABLE 25

MOST PROMISING AIRCRAFT OPTIONS FOR REDUCING FUEL CONSUMPTION

	Selected Aircraft Options	
Number of Study Options	With Fuel Constraints	Without Fuel Constraints
13 Retrofits	DC-8-50 DR DC-8-61 DR DC-10-10 R	DC-8-50 DR DC-8-61 DR
7 Derivatives	DC-9-30 D3 DC-10-10 D	DC-9-30 D1 DC-9-30 D3 DC-10-10 D
12 New Near-Term	N80-2.15$_{30}$ N80-2.30$_{30}$ N80-4.30$_{30}$ N80-4.30$_{60}$	N80-2.15$_{30}$ N80-4.30$_{30}$ N80-4.30$_{60}$

TABLE 26

1990 PROJECTED POTENTIAL MARKET SIZES

Selected Aircraft Options		Potential U.S. Domestic Aircraft Market
Derivatives		
DC-9-30D1		500 - 550
DC-9-30D3		175
DC-10-10D		90
New Near-Term Aircraft		
N80-2.15$_{30}$		60
N80-2.30$_{30}$	(Fuel Constrained Environment Only)	45
N80-4.30$_{30}$		150
N80-4.30$_{60}$		120

Market sizes for the derivative options were rewarding, especially in terms of the fuel savings potential they offer, as well as the economic viability they would provide the manufacturer. It should be pointed out that the market sizes estimated in this study did not include the potential for further aircraft sales for use in the fleets of the foreign carriers.

The market requirements for the N80 airplanes were too low to establish a viable new aircraft program. However, it should be remembered that the majority of the selected N80 options were not needed by the market until 1984-1985, and therefore, a market size determined in 1990 is somewhat premature. This points to the desireability of delaying introduction of the N80's until 1985-1990.

The market size for the N80-2.15$_{30}$ was not as large as anticipated due to the competition from the 117 seat derivative DC-9, designated the DC-9-30 D1. This airplane option was better sized for the market growth forecasted in this study. For this reason, as well as the large number of short haul airline routes domestically, it would be worthwhile to study a fuel conservative

125-150 seat, 1500 nautical mile range N80 aircraft in the U.S. domestic system. This airplane might prove to be highly viable in the market by replacing older DC-9/B737/B727 aircraft types and producing significant fuel savings within the system.

6.3.4 Fuel Consumption and Savings - The fleet forecasts developed represented the U.S. domestic air transportation system in both a restricted fuel as well as an unlimited fuel environment. Results of the fleets' fuel requirements were evaluated to assess the potential fuel savings possible over the DC-Jet network and to define reasonable bounds around the potential U.S. domestic jet-fuel demand through 1990.

As expected, the baseline scenario with fuel at 15¢ per gallon demanded the most jet fuel, 144.5 million tons, over the forecast period, 1973-1990. The lowest fuel consumption at both study fuel prices was achieved by the mixed fleet of selected retrofits, derivatives, and new near-term aircraft performing the same or more RPM's than the baseline scenarios with hub constraints, 131.3 million tons and 129.3 million tons at fuel prices of 30¢ and 60¢ per gallon, respectively.

The fuel consumed by the fleet forecasted for each scenario is given in Table 27. For comparison purposes, the cumulative time period, 1980-1990, was included since the majority of the aircraft options were introduced to the market in 1980. The fuel savings over this period more realistically represent the actual fuel savings that could be achieved through the use of the selected study options.

The potential for fuel savings with each succeeding fleet forecast based upon different offerings of aircraft options under both fuel environments is shown in Table 28. The fuel consumed in the various fleet forecasts were compared for efficiency on the basis of pounds of fuel burned per RPM, since the RPM's for each scenario were different.

From Table 28, it can be seen that fuel conserving operating procedures offered as much as a 5% reduction in fuel burned over the study period, and over 6.5% in 1990 alone. Assuming an improved ATC system became operational in 1980, the fuel savings attributable to this improvement alone equalled almost 4% in 1990 as well as over the period 1980-1990. The total potential fuel savings from fuel conserving operational procedures and an advanced ATC were over 10% in the same time periods. These savings equate to over 9 million tons during 1980-1990 and almost a million tons in the year 1990 alone.

The three most promising modifications options selected by the market in this study saved almost 1.5% fuel during 1973-1990. When the selected derivative options were added to the fleet, fuel savings improved substantially to 7% during 1980-1990 and almost 8.5% in 1990 alone, or a savings of over 5 million tons from 1980-1990.

Fuel savings continued to improve with the addition of each group of selected options: the modification options alone, the mods plus derivatives, and then the mods, derivatives, and N80's, as can be seen in Table 28. It should be noted that in each scenario the existing aircraft in the fleet that were still in production in 1973 were always offered to the market along with the different offerings of fuel conserving aircraft options.

TABLE 27

COMPARATIVE FUEL BURNED (MILLIONS OF TONS)

TOTAL DC-JET ROUTE NETWORK

Scenario Description & Fuel Price (¢/Gal)	Annual 1980	Annual 1990	Cumulative 1980-1990	Cumulative 1973-1990
BASELINE SCENARIOS				
15¢	7.229	10.130	95.494	144.457
30¢	7.229	10.068	95.124	144.076
60¢	7.229	10.061	94.974	143.979
HUBS @ 30¢	7.158	9.280	90.948	139.592
HUBS @ 60¢	7.158	9.169	90.550	139.120
Fuel Constrained @ 30¢	6.770	6.776	74.507	122.181
Consv. Flt. Opers. @ 60¢	6.708	8.541	84.720	132.088
Consv. Flt. Opers. + 1980 ATC @ 60¢	6.432	8.200	81.410	128.530
UNLIMITED FUEL SCENARIOS				
Modifications @ 30¢	6.888	9.144	89.188	137.552
Derivatives* @ 30¢	6.935	8.805	85.741	134.231
N80s** @ 30¢	6.749	8.365	82.844	131.341
N80s** @ 60¢	6.599	8.199	81.291	129.312
N80s** - 55% L.F. @ 30¢	6.955	8.668	85.006	133.637
N80s** - 70% L.F. @ 30¢	6.749	7.380	75.909	124.406
CONSTRAINED FUEL SCENARIOS				
Modifications @ 30¢	6.455	6.756	73.514	120.795
Derivatives* @ 30¢	6.452	6.679	72.597	119.323
N80s** @ 30¢	6.312	6.550	71.103	117.829
N80s** @ 60¢	6.026	6.528	69.611	116.223

*Derivatives = Modifications + Derivatives
**N80s = Modifications + Derivatives + N80s

NOTE: Fuel burned on DC-Jet network in 1973 = 6.784 million tons

TABLE 28

COMPARATIVE FUEL SAVINGS PER RPM (PERCENT)

TOTAL DC-JET ROUTE NETWORK

Scenario Description & Fuel Price (¢/Gal)	Cumulative 1973-1990	Cumulative 1980-1990	Annual 1990
Relative to hub-constrained scenarios @ 30¢ and 60¢ per gallon			
BASELINE SCENARIOS			
Fuel Constrained @ 30¢	-2.9	-6.0	-6.2
Consv. Flt. Opers. @ 60¢	4.9	6.3	6.6
Consv. Flt. Opers. + 1980 ATC @ 60¢	7.5	10.1	10.5
UNLIMITED FUEL SCENARIOS			
Modifications @ 30¢	1.4	2.0	1.4
Derivatives* @ 30¢	4.7	7.0	8.3
N80s** @ 30¢	6.8	10.2	13.4
N80s** @ 60¢	7.6	11.1	14.8
N80s** - 55% L.F. @ 30¢	4.3	6.8	9.5
N80s** - 70% L.F. @ 30¢	13.0	19.3	26.2
CONSTRAINED FUEL SCENARIOS			
Modifications @ 30¢	3.2	5.4	3.6
Derivatives* @ 30¢	4.5	7.3	6.3
N80s** @ 30¢	8.1	12.5	15.6
N80s** @ 60¢	8.1	12.6	14.3
Relative to baseline fuel constrained scenario @ 30¢ per gallon			
CONSTRAINED FUEL SCENARIOS			
Modifications @ 30¢	5.9	8.5	9.2
Derivatives* @ 30¢	7.3	10.3	11.8
N80s** @ 30¢	10.7	15.4	20.5

*Derivatives = Modifications + Derivatives
**N80s = Modifications + Derivatives + N80s

The highest fuel savings were achieved with a mixed fleet of aircraft options (mods, derivatives, plus N80's) selected for a fuel price of 60¢ per gallon. This fleet reduced jet fuel consumption by almost 8% over the total forecast period, over 11% during 1980-1990, and by nearly 15% in the year 1990 alone. These fuel savings produced by the mixed fleet of selected aircraft options amounted to 400 million gallons in the year 1990 alone and over 3 billion gallons from 1973-1990 when compared with the baseline hub-constrained fleet forecast for a fuel price of 60¢ per gallon. Fuel savings achieved with the mixed fleet selected by the market when fuel was 30¢ per gallon were approximately 1% less in each of the time periods than they were with the fleet selected for fuel at 60¢.

When the goal load factor was allowed to increase from 58% to 70%, the fuel savings achieved with a market-selected fleet (mods, derivatives, plus N80's) of the aircraft options, at a fuel price of 30¢ per gallon were significant. Fuel savings of 9% during 1980-1990 and 13% during 1990 alone were produced above those savings already provided by the mixed fleet selected at the same fuel price but with the study load factor of 58%.

Results for the comparable fleet forecasts under a fuel allocated environment were very similar, although the fuel savings in percentages were generally higher as shown in Table 28. In the fuel constrained scenarios, the market selected those aircraft types which maximized profits, within the total fuel allocation. Thus, these fleets tended to perform the greatest number of RPM's per pound of fuel. When fuel savings achieved with the fuel constrained fleets were compared with those for the unlimited fuel fleets, this higher fuel efficiency generally resulted in higher percentage fuel savings.

SECTION 7.0

U.S. INTERNATIONAL MARKET

The international market operated by the U.S. scheduled airlines was also studied in order to determine the anticipated fuel demand and fleet requirements for these carriers during the period 1974-1990. Several possible long-range derivatives of existing aircraft as well as six all-new near-term aircraft (N80's) were analyzed in terms of their economic viability and potential fuel savings relative to the baseline 1974 airplanes already in the airline fleets. In accomplishing this task, alternative fleet forecasts were developed to screen these possible aircraft options against the U.S. international market requirements. The results of the forecasts were then compared both economically and operationally. As in the domestic study, the criteria used in comparing viability included operating costs, potential airline profit, revenue passenger-miles flown, fuel saved, as well as forecasted fleet size and mix.

7.1 Study Approach

The U.S. international scheduled market and its characteristics were carefully reviewed, and a forecast was made of the potential traffic demand in this market from 1974-1990. A baseline operational scenario was developed to reflect the operating environment of the U.S. international carriers during 1974. Next, alternative operational scenarios were created by varying one or more of the constraints in this baseline scenario in order to determine the impact of these constraints on fuel burned and saved, profit generated, as well as fleet size and mix. The constraints that were varied included fuel price, goal load factor, fuel availability, as well as the grouping of aircraft options offered to the market.

As in the domestic study, the Performance Evaluation Technique, was used to determine the alternative fleet forecasts for each operational scenario. The objective criterion was to maximize airline profits through the appropriate choice of offered aircraft options under a particular operating environment.

7.2 Study Market Characteristics

The city pairs served by the U.S. international scheduled carriers as well as the available seat-miles, departures, and aircraft types by city pair were collected from the August 1974 Official Airline Guide. Based upon the CAB's Uniform Systems of Accounts - Part 241, the U.S. international market excluded operations to Hawaii and Alaska as well as all Canadian transborder services.

7.2.1 Available Seat-Miles - The August 1974 available seat-miles were adjusted to an annual basis using the CAB's Seasonally Adjusted Data Report for the scheduled international trunks. Since August represented 9.6% of the annual 1974 ASM's, the U.S. international scheduled carriers generated over 63 billion ASM's in 1974.

The actual 1974 available seat-miles were adjusted by aircraft type to reflect the CAB average seating density for that aircraft type in U.S. international service. Use of the average aircraft seating configurations increased the 1974 ASM's to 65 billion and decreased the actual 1974 load factor of 53% to 51.4%. A planning or goal load factor of 58% was established

based on Douglas estimates of an average load factor for the U.S. international scheduled carriers during the 1976-1990 study period. The actual available seat-miles generated during the forecast period varied for each operating scenario and fleet studied.

7.2.2 Revenue Passenger-Miles - An RPM demand of 33.4 billion in 1974 was determined using the actual load factor of 53% applied to the actual 1974 ASM's. Then the revenue passenger-miles were forecast from 1974 to 1990 using an average annual growth rate of 4.6%. This growth rate represents Douglas' estimate of a realistic average over this period for the U.S. international scheduled carriers. Using this growth rate, the U.S. international RPM's grew from 33.4 billion in 1974 to almost 69 billion by 1990, a 100% increase over the period (Figure 19).

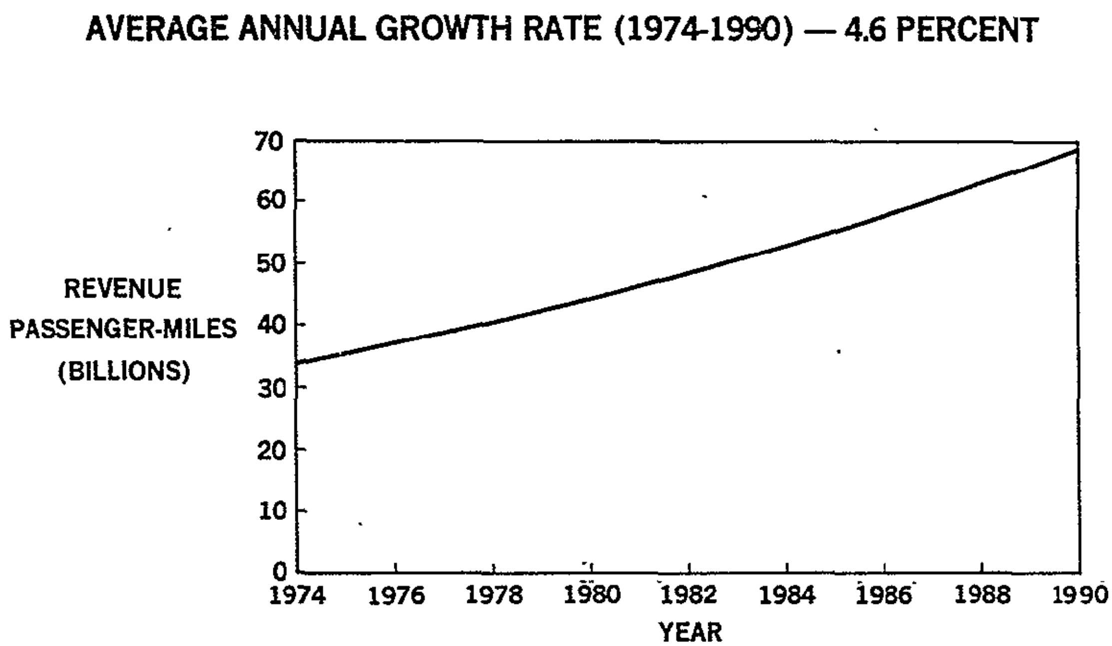


FIGURE 19. U.S. SCHEDULED INTERNATIONAL REVENUE PASSENGER-MILE FORECAST

7.3 Airline Consultations

Basic to this study was a review of the general fuel cost trends, the operational realism of various means of conserving fuel, and the anticipated growth in the market for the U.S. international scheduled carriers. To assure that this market study accurately reflected the actual operations of the carriers, three U.S. international airlines were contacted: Pan American World Airways, Trans World Airlines, and Northwest Airlines.

7.4 Aircraft Characteristics and Direct Operating Costs

The study of aircraft designed for the international routes of the U.S. carriers was conducted independently by Douglas, without the assistance of an airline contractor. For this reason, and also because the international study included Boeing and Lockheed airplanes in addition to the Douglas airplanes, the block fuel, block time, and DOC characteristics for the study aircraft were derived from a statistical reduction of annual 1974 Civil Aeronautics Board (CAB) and August 1974 Official Airline Guide (OAG) data.

7.4.1 Baseline Aircraft in the International Market - Passenger versions of Boeing, Lockheed, and Douglas turbofan commercial transports currently in the fleets of the U.S. international scheduled carriers were chosen as the baseline aircraft. These fleets included aircraft from the following families: DC-8, DC-9, DC-10, L1011, B707, B720, B727, and B747. The actual baseline models and their characteristics are given in Table 29. The general characteristics were based upon manufacturers' published data, while the seat densities were based on the average 1974 capacities reported by the airlines to the CAB.

TABLE 29

BASELINE AIRCRAFT CHARACTERISTICS

International Study Aircraft	No. of Seats	TOGW (lb)	Study OEW (lb)	Cruise Mach Number	Engines (No., Type, TSLS/Eng (lb))	Design Range (NM)
DC-8-50	148	300,000	132,000	.82	4, JT3D-3B, 18,000	4180
DC-8-62	164	350,000	145,000	.82	4, JT3D-3B, 18,000	5250
DC-9-30	97	108,000	57,900	.80	2, JT8D-7, 14,000	1660
DC-10-10/L1011	240	430,000	237,200	.85	3, CF6-6D, 40,100	3940
B707-100B	130	257,000	123,200	.82	4, JT3D-3B, 18,000	3720
B707-300B	153	327,000	137,200	.82	4, JT3D-3B, 18,000	5550
B707-300C	146	334,000	145,000	.82	4, JT3D-3B, 18,000	5460
B720B	119	235,000	119,000	.82	4, JT3D-3B, 18,000	3150
B727-100	107	169,000	88,500	.82	3, JT8D-7, 14,000	2210
B727-200	131	172,000	97,400	.84	3, JT8D-9, 14,500	1680
B747-100	368	735,000	364,000	.85	4, JT9D-7, 47,000	4650

7.4.2 Derivative Aircraft Options - Four derivative aircraft were studied for the future international market. The DC-10-10D is a shortened twin-engine version of the DC-10-10 with an all-new supercritical wing. The DC-10-30D1 is a modification of the existing intercontinental range DC-10-30. Relative to the DC-10-10, the DC-10-30D1 has extended wing tips, center-wing fuel tanks, higher thrust engines, and general drag and weight reduction items. The DC-10-30D2 involves a 30 foot fuselage stretch, winglets, and general drag and weight reduction programs. The B747D also includes general drag and weight reductions, and has accommodations for 32 additional passengers on the upper deck. General characteristics of the derivative aircraft are given in Table 30. The derivative aircraft block fuel, block time, and DOC characteristics were derived by adjusting the baseline aircraft data to reflect the derivative design changes.

7.4.3 New Near-Term (1980) Aircraft - Two intercontinental range families of new near-term aircraft were also studied. The airplanes designed in each N80 aircraft family were optimized for either maximum fuel efficiency (minimum fuel burned) or minimum DOC at a fuel price of 30¢ or 60¢ per gallon. This resulted in six all-new aircraft options. The operational block fuel, block time, and DOC characteristics for the N80 aircraft were developed on the same bases as those for the derivative aircraft options, in order to assure compatibility with CAB operational data levels. Tables 31 and 32 present the general characteristics of the study international N80 airplanes.

TABLE 30

DERIVATIVE AIRCRAFT OPTION CHARACTERISTICS

AIRCRAFT CHARACTERISTICS	DC-10-10D	DC-10-30D1	DC-10-30D2	B747D
Number of Seats	199	252	327	400
TOGW (lb)	283,000	555,000	572,000	738,000
OEW (lb)	160,800	267,600	274,700	370,000
Cruise Mach Number	.82	.85	.85	.85
Engines: Number	2	3	3	4
Type	CF6-50	CF6-50C	CF6-50J	JT9D-7
TSLS/Eng (lb)	46,600	51,000	54,000	47,000
Design Range (NM)	3,050	5,470	4,710	4,900

7.5 Indirect Operating Costs

To be consistent with the domestic study, the 1969 Lockheed Committee IOC method was also used in the international study. The formulas were updated to estimate 1974 cost levels and the coefficients used reflected U.S. international operations.

7.6 Operating Profit

In order to select those fuel conserving aircraft options that maximized the fleet's operational and economic performance, the operating profit for each alternative fleet forecast was determined. Operating profit was defined as the total operating revenue from scheduled passenger and cargo services less the total operating costs.

The passenger revenue generated by a particular fleet of aircraft over the forecast period 1974-1990 was based upon the airline revenue data documented in "Airline Industry Data - U.S. Trunkline Carriers and Pan American," June 5, 1975. The development of the Revenue Equations used is documented in Section 4.6.1 of Volume II. Cargo revenue as in the Domestic RECAT Study was estimated at 3% of the total passenger revenue.

7.7 Study Scenarios

Eleven alternative operating scenarios were developed, and each scenario was offered against the baseline 1974-1990 passenger demand. Table 33 describes each scenario studied in terms of its operational constraints and Table 34 lists the competitive aircraft options offered in each scenario. The scenarios investigated were broken down into two groups.

- 2 baseline operating scenarios with baseline aircraft only
- 9 alternative operating scenarios to select the most promising aircraft options
  - derivative aircraft
  - new near-term (1980) airplanes

7.8 Baseline Operating Scenarios

A baseline scenario (No. 1, Tables 33 and 34) was developed to reflect the airline environment in which the U.S. international carriers operated during 1974. This scenario included 1974 operating procedures, a constant dollar

TABLE 31

OPTIMUM N80-2.55 AIRCRAFT CHARACTERISTICS

4 CFM-56 Type Engines, 201 Passengers, 5,500 NM Range

		OPTIMIZATION PARAMETER		
		DOC_{30}	DOC_{60}	BLOCK FUEL
Takeoff Gross Weight	Lb	375,100	367,500	386,900
Operational Empty Weight	Lb	184,400	186,000	208,900
Cruise Mach Number		0.82	0.78	0.70
Block Time (1)	Hr	12.05	12.64	14.00
Block Fuel (1)	Lb	136,060	127,590	124,330
Critical Field Length	Ft	8,216	8,850	8,316
Approach Speed	KEAS	117.5	116.1	103.6
Thrust Per Engine Uninstalled	Lb	22,720	20,240	17,780
Direct Operating Cost (1)	¢/Seat-NM			
@ 15¢ Per Gallon		1.309	1.349	1.511
@ 30¢ Per Gallon		1.567	1.591	1.749
@ 60¢ Per Gallon		2.082	2.074	2.225
Geometry				
Aspect Ratio		9.6	11	15.5
Quarter Chord Sweep	Deg	33	30.7	3.2 (2)
Average Thickness-To-Chord Ratio		0.137	0.136	0.13
Taper Ratio		0.30	0.30	0.30
Wing Area (3)	Ft^2	2,850	2,850	3,410
Fuel Use @ 1,000 NM	BTU/ASNM	2,128	2,017	2,017

(1) 100 Percent Load Factor at Design Range
(2) Straight Rear Spar
(3) Fuel Volume Limited

TABLE 32

OPTIMUM N80-4.55 AIRCRAFT CHARACTERISTICS

4 CF6-6D Type Engines, 404 Passengers, 5,500 NM Range

		OPTIMIZATION PARAMETER		
		DOC_{30}	DOC_{60}	BLOCK FUEL
Takeoff Gross Weight	Lb	704,700	701,400	747,600
Operational Empty Weight	Lb	361,200	368,400	420,400
Cruise Mach Number		0.82	0.79	0.70
Block Time (1)	Hr	12.12	12.48	13.95
Block Fuel (1)	Lb	238,170	228,690	223,880
Critical Field Length	Ft	11,000	11,000	11,000
Approach Speed	KEAS	118.4	118.1	112.0
Thrust Per Engine Uninstalled	Lb	40,240	37,290	35,160
Direct Operating Cost (1)	¢/Seat-NM			
@ 15¢ Per Gallon		0.947	0.968	1.100
@ 30¢ Per Gallon		1.169	1.182	1.311
@ 60¢ Per Gallon		1.612	1.610	1.735
Geometry				
Aspect Ratio		9.5	11.0	15.5
Quarter Chord Sweep	Deg	32.5	29.0	3.2 (2)
Average Thickness-To-Chord Ratio		0.140	0.139	0.135
Taper Ratio		0.30	0.30	0.30
Wing Area	Ft^2	5,150	5,050	5,600
Fuel Used @ 1,000 NM	BTU/ASNM	1,842	1,846	1,848

(1) At Design Range, 100 Percent Load Factor
(2) Straight Rear Spar

TABLE 33

DEVELOPMENT OF FLEET FORECASTS - RUN SCHEDULE
OBJECTIVE - MAXIMIZE AIRLINE PROFIT

Scenario No.	FLEET INVENTORY OPTIONS			LOAD FACTOR		FUEL AVAILABILITY		FUEL PRICE		Scenario Description
	Exist A/C	Deriv. A/C	New Near Term	Goal 58%	Inc. L.F. 70%	No Limit	1974 Level	30¢	Inc. Price 60¢	
1	X			X		X		X		Baseline 30¢
2	X	X		X		X		X		Screen derivatives 30¢
3	X	S		X		X		X		Selected derivatives 30¢
4	X.	S	X	X		X		X		Screen selected derivatives with N80's 30¢
5	X			X		X			X	Baseline 60¢
6	X	X		X		X			X	Screen derivatives 60¢
7	X	S		X		X			X	Selected derivatives 60¢
8	X	S	X	X		X			X	Screen selected derivatives with N80's 60¢
9	X	S	X		X	X			X	Screen derivatives, N80's @ 70% L.F., 60¢
10	X	S	S		X	X			X	Selected derivatives +N80's @ 70% L.F., 60¢
11	X	S	X		X		X		X	Screen selected derivatives with N80's @ 70% L.F. w/fuel constraints, 60¢

S = Selected Options

TABLE 34

AIRCRAFT TYPES OFFERED IN EACH U.S. INTERNATIONAL SCENARIO

Scenarios

AIRCRAFT TYPE		1	2	3	4	5	6	7	8	9	10	11
	Fuel Price	← 30¢ →				← 60¢ →						
DC-8*		X	X	X	X	X	X	X	X	X	X	X
DC-8-62		X	X	X	X	X	X	X	X	X	X	X
DC-9-30		X	X	X	X	X	X	X	X	X	X	X
DC-10 / L1011		X	X	X	X	X	X	X	X	X	X	X
B707-300B		X	X	X	X	X	X	X	X	X	X	X
B707-300C		X	X	X	X	X	X	X	X	X	X	X
B727-100		X	X	X	X	X	X	X	X	X	X	X
B727-200		X	X	X	X	X	X	X	X	X	X	X
B747		X	X	X	X	X	X	X	X	X	X	X
DC-10-10D			X	X	X		X	X	X	X	X	X
DC-10-30M			X				X			X		
DC-10-30D			X	X	X		X	X	X	X	X	X
B747D			X				X			X		
$N80\text{-}2.55_{30}$					X				X	X		X
$N80\text{-}2.55_{60}$					X				X	X	X	X
$N80\text{-}2.55_{MF}$					X				X	X		X
$N80\text{-}4.55_{30}$					X				X	X		X
$N80\text{-}4.55_{60}$					X				X	X		X
$N80\text{-}4.55_{MF}$					X				X	X		X
TOTAL NUMBER OF AIRCRAFT TYPES		9	13	11	17	9	13	11	17	19	12	17

* Includes DC-8-50, B707-100, B720B

fuel price of 30¢ per gallon, 1974 passenger yields, a goal load factor of 58%, and 1974 frequencies as a minimum. No maximum frequency levels were established for this preliminary international market study. Also, the availability of fuel was unlimited throughout the study period, 1974-1990. Only the existing aircraft types in this market still in production in 1974 were available for purchase to meet subsequent aircraft demand through 1990. This first baseline scenario, based on the assumed average annual RPM growth rate of 4.6%, establishes an upper limit on fuel demand for the U.S. international carriers over the forecast period since fuel availability was unlimited and no fuel conserving aircraft options were allowed to serve the market.

The second baseline scenario (No. 5) reflected the same operating environment as the first scenario except that the fuel price was 60¢ per gallon. The fleet forecast results from both these baseline scenarios were used as the reference cases against which the results achieved under the alternative operating scenarios discussed in Section 7.9 were measured.

7.9 Alternative Operating Scenarios

Nine alternative operating scenarios were developed in which the operational constraints in the baseline scenarios were varied during the 1974-1990 forecast period. These changes involved fuel availability, load factor, as well as the different offerings of aircraft options. Only in scenario No. 11 was the fuel supply limited. In this case a fuel supply equivalent to the total fuel burned by the U.S. international fleet in 1974 was allotted to the market each year through 1990. The effects of these changes on both fuel savings and fleet requirements as well as other operating statistics were then assessed.

In each of these scenarios, subsequent aircraft needs were met not only with additional numbers of existing 1974 aircraft types, but also with the fuel conserving options under study. The different offerings of aircraft options available for selection by the market in each scenario are given in Table 34. It should be noted that in each scenario the existing aircraft in the fleet that were still in production in 1974 were always offered to the market along with the different offerings of fuel conserving aircraft options.

7.10 Summary of Fleet Forecast Results

The fleet forecast results for this U.S. international market study have been documented for the years 1976-1990 even though the RPM's as well as fleet size and mix were actually forecasted from 1974-1990 for each scenario. This was done in order to focus on the future fuel savings and profit improvements possible with the use of the most promising fuel conserving aircraft options in the fleets.

7.10.1 Revenue Passenger-Miles - The fleets required for each scenario throughout the forecast period performed all the forecasted revenue passenger-miles from 1974-1990 with the exception of the fleet selected under the fuel constrained environment. In 1990 only 78% of the potential RPM's were flown under this scenario, and over the 1976-1990 time period only 88% of the RPM's were performed.

7.10.2 Fleet Sizes - The required fleet size for each scenario by selected years are given in Table 35. Each fleet is composed of a different number and mix of aircraft types, but the total fleet size under each scenario does not vary substantially. The 1980 fleet size for the U.S. international carriers was estimated at 260-265 aircraft, an increase from 230 airplanes in the fleet in 1974. By 1990 the required fleet grew to 320-330 airplanes.

The number of aircraft demanded in 1990 with a goal load factor of 70% was 287 versus 321 with a 58% load factor. Also the fleet size required under a fuel constrained scenario was considerably smaller, 226 airplanes in 1990, due to the lack of ability to perform all the RPM demand within the allocated fuel levels.

TABLE 35

U.S. INTERNATIONAL FLEET SIZES BY YEAR

Scenario Description & Fuel Price (¢/Gal)	1976	1980	1985	1990
Baseline @ 30¢	241	269	336	388
All Derivatives @ 30¢	241	261	289	334
Selected Derivatives @ 30¢	241	261	291	328
Selected Derivatives, N80's @ 30¢	241	258	288	322
Baseline @ 60¢	240	269	331	364
All Derivatives @ 60¢	240	263	287	325
Selected Derivatives @ 60¢	240	263	284	328
Selected Derivatives, N80's @ 60¢	240	261	285	321
N80s* + 70% L.F. @ 60¢	240	261	263	287
N80s* + 70% L.F. + Fuel Alloc. @ 60¢	230	230	227	226

*N80's = Derivatives + N80's

7.10.3 Selected Aircraft Options - Although the types and numbers of each airplane required in each scenario varied, several of the ten aircraft options were selected in sufficient quantity by the market in almost every scenario. Out of the four derivative aircraft studied, two were selected as the most promising for fuel conservation, as well as being the most economically and operationally viable under the two fuel environments examined.

Of the six N80 airplanes, four were selected in the various scenarios, but no all-new aircraft was really viable nor flexible enough to be desired in a scenario other than the ones that matched its particular design characteristics.

Table 36 shows the potential U.S. international market demand for each of the six selected options. As can be seen, both derivative options achieved feasible market sizes, while no selected N80 aircraft was heavily demanded by the market under any of the simulated airline environments studied. It should be noted that the potential market sizes given in the table do not include the demand from foreign carriers for these selected aircraft options.

TABLE 36

1990 POTENTIAL MARKET SIZES

Selected Aircraft Options	U.S. International Aircraft Market
Derivatives	
DC-10-10D	50
DC-10-30D2	60
New Near-Term Aircraft	
$N80\text{-}2.55_{30}$	15
$N80\text{-}2.55_{60}$	14
$N80\text{-}2.55_{MF}$	21
$N80\text{-}4.55_{30}$	22

7.10.4 Profit Improvement - In comparing the viability of the aircraft options, the profit achieved by each fleet due to the addition of selected aircraft options was compared to the profit generated by the baseline fleet forecasts at fuel prices of 30¢ and 60¢ per gallon respectively, as shown in Table 37. Profits in the simulated airline environments improved significantly when the selected aircraft options became available in the fleets.

TABLE 37

COMPARATIVE FLEET FORECAST PROFIT RESULTS ($ Per RPM)

Scenario Description & Fuel Price (¢/Gal)	Cumulative Profit Improvement (Percent)	
	1976-1990	1980-1990
Relative to Baseline Scenario with Fuel at 30¢ Per Gallon		
Selected Derivatives @ 30¢	5.6	6.8
Selected Derivatives, N80's @ 30¢	7.0	8.5
Relative to Baseline Scenario with Fuel at 60¢ Per Gallon		
Selected Derivatives @ 60¢	33.4	35.2
Selected Derivatives, N80's @ 60¢	38.5	40.5
N80's* + 70% L.F. @ 60¢	147.3	154.9
Relative to N80's* Scenario, 70% L.F., with Fuel at 60¢ Per Gallon		
N80's* + 70% L.F. + Fuel Alloc. @ 60¢	3.6	5.9

*N80's = Derivatives + N80's

7.10.5 Fuel Consumption and Savings - The fuel conserving fleet forecasts were developed to represent the U.S. international air transportation system in both an unlimited as well as a restricted fuel environment. The fuel consumed by the fleet forecasted under each scenario is given in Table 38. Since the majority of the aircraft options were introduced to the market in 1980, the fuel savings over the 1980-1990 time period more realistically represented the actual fuel savings that could be achieved through the use of the selected study options. In the fuel restricted scenario, the 1974

fuel allocation level by 1990 provided only 58% of the fuel required by a mixed fleet of selected options (baseline airplanes, derivatives, and N80's) in an unconstrained fuel environment that year.

TABLE 38

COMPARATIVE FUEL CONSUMPTION (Millions of Tons)

Scenario Description & Fuel Price (¢/Gal)	Annual		Cumulative	
	1980	1990	1976-1990	1980-1990
Baseline @ 30¢	5.770	9.017	101.097	79.267
All Derivatives @ 30¢	5.723	8.062	96.699	74.869
Selected Derivatives @ 30¢	5.723	8.044	96.534	74.704
Selected Derivatives and N80's @ 30¢	5.714	8.031	96.560	74.730
Baseline @ 60¢	5.773	9.005	101.086	79.239
All Derivatives @ 60¢	5.733	8.043	96.648	74.801
Selected Derivatives @ 60¢	5.733	8.036	96.510	74.663
Selected Derivatives and N80's @ 60¢	5.723	7.971	96.108	74.261
N80's* + 70% L.F. @ 60¢	5.723	6.565	86.573	64.726
N80's* + 70% L.F. + Fuel Alloc. @ 60¢	4.980	5.042	75.033	54.865

*N80's = Derivatives + N80's

As expected, the baseline scenarios with fuel prices of 30¢ and 60¢ per gallon, and fleets consisting of only baseline aircraft types through 1990 demanded the most jet fuel, 101.1 million tons, over the study period, 1976-1990. The lowest fuel consumption, 86.6 million tons, was achieved by the mixed fleet of selected derivatives and new near-term aircraft performing at a 70% load factor in a non-fuel constrained scenario. In a static airline environment, the difference in fuel burned with the higher goal load factor was 18% or 1.4 million tons less in 1990 alone.

The potential for fuel savings with each succeeding fleet forecast based upon different offerings of aircraft options under both fuel environments is shown in Table 39.

TABLE 39

COMPARATIVE FUEL SAVINGS PER RPM (PERCENT)

Scenario Description & Fuel Price (¢/Gal)	Annual	Cumulative	
	1990	1976-1990	1980-1990
Relative to Baseline Scenario with Fuel at 30¢ Per Gallon			
Selected Derivatives @ 30¢	10.8	4.5	5.8
Selected Derivatives and N80's @ 30¢	10.9	4.5	5.7
Relative to Baseline Scenario with Fuel at 60¢ Per Gallon			
Selected Derivatives @ 60¢	10.8	4.5	5.8
Selected Derivatives and N80's @ 60¢	11.5	4.9	6.3
N80's + 70% L.F. @ 60¢	27.1	14.4	18.3
Relative to N80's Scenario, 70% L.F., with Fuel at 60¢ Per Gallon			
N80's* + 70% L.F. + Fuel Alloc. @ 60¢	1.3	1.6	2.9

*N80's = Derivatives and N80's

When the selected derivative options were added to the fleet of existing airplanes, at either study fuel price, fuel savings improved substantially to almost 6% during 1980-1990 and almost 11% in 1990 alone, or a savings of over 4.6 million tons from 1980-1990. Fuel savings did not improve significantly with the addition of the selected new near-term (N80's) options since few N80's were desired by the market.

When the goal load factor was allowed to increase from 58% to 70%, the fuel savings achieved with a market-selected fleet of derivatives plus N80's at a fuel price of 60¢ per gallon were substantial. Fuel savings of 13% during 1980-1990 and 17% during 1990 alone were obtained above those savings already provided by the mixed fleet selected at the same fuel price but with the study load factor of 58%, showing the strong impact of higher load factors on fuel efficiency.

SECTION 8.0

TURBOPROP AIRCRAFT

Potential improvements in fuel use due to advances in turboprop propulsion system technology and wing aerodynamics were studied on a DC-9-30 baseline aircraft. The turboshaft engine performance used in this study represents 1985 engine technology, as provided in recent Pratt & Whitney STS 476 and Allison PD 370 studies. The propeller performance is based upon the Hamilton Standard propfan, which is a multi-bladed, variable pitch propeller using swept blade tips and supercritical blade sections. Aerodynamic improvements include a supercritical wing section, greater sweep, and a higher aspect ratio wing.

Three derivative aircraft were studied. The DC-9-30D4 has aft fuselage-mounted turbofan engines and an all new supercritical wing. The DC-9-30D5 has two propfan engines mounted on a strengthened, conventional DC-9-30 wing. The DC-9-30D6 has two propfan engines, mounted on a strengthened DC-9-30D4 supercritical wing.

8.1 Configuration Studies

The new wing and/or powerplant were incorporated into the three derivative aircraft with a minimum of configuration changes to the baseline DC-9-30. The derivative airplanes were not resized to the same payload-range specifications as the baseline aircraft. Instead, the gross weight and payload were held constant; the supercritical wing was sized to meet the approach speed capability of the DC-9-30; the empty weight and fuel capacity were changed as required; and the range capability was determined as the result of the combination of fuel capacity changes and improved technology. The two propfan aircraft were rebalanced to allow for the forward location of the powerplants, and their vertical tails were resized for the one-engine-out emergency condition.

Figures 20 and 21 show the DC-9 propfan aircraft configurations. The propfan powerplants are located at 41% semi-span, and are mounted forward of the wing structural box to facilitate access and removal. This spanwise location provides a propeller tip-to-fuselage clearance of 56% of the propeller diameter, and the propeller slipstream does not wet the ailerons. However, at this spanwise location, the asymmetric thrust in the one-engine-out condition requires a larger vertical tail and a dual hinge rudder. Various nacelle and landing gear arrangements were studied. The overwing nacelle configuration with landing gear in the fuselage results in the slimmest nacelle and shortest gear.

8.2 Propfan Aircraft Performance

Specifications for takeoff, approach, and cruise performance of the propfan aircraft were chosen to match baseline DC-9-30 performance. The cruise condition for sizing the propfan installation was 0.80 Mach at 30,000 feet at maximum cruise weight. The performance study included two constant altitude cruise conditions: 30,000 ft. altitude at 0.80 Mach, and 15,000 ft. altitude at 350 knots (DC-9-30 placard speed).

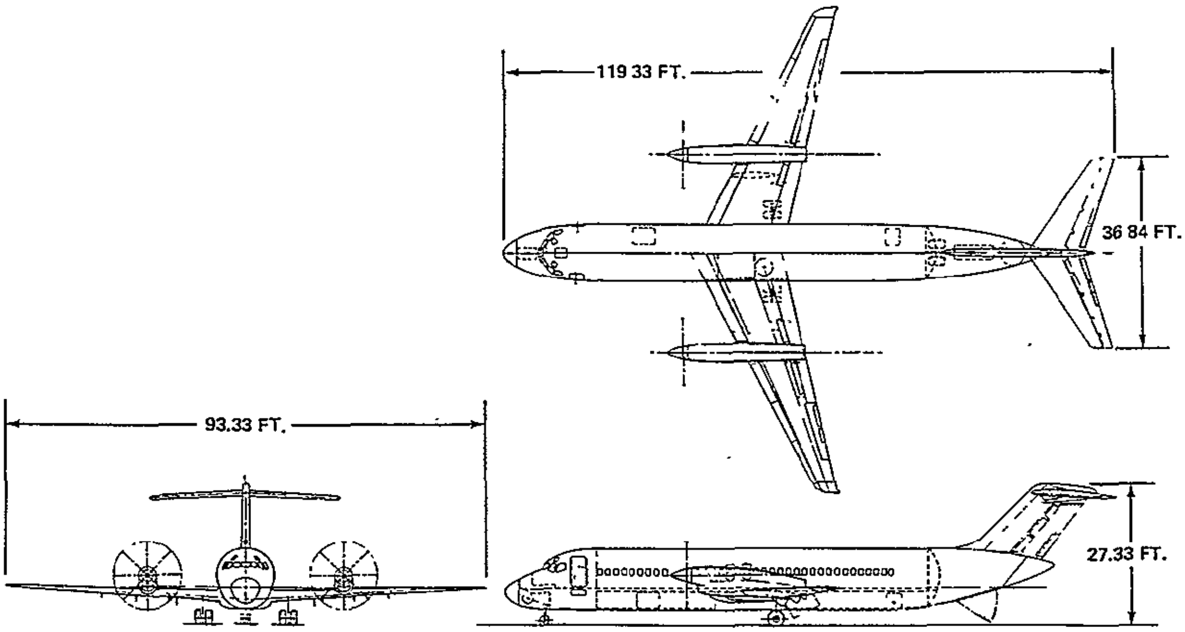


FIGURE 20. GENERAL CONFIGURATION, DC-9-30D5 PROPFAN

ITEM	WING*	HORIZONTAL TAIL A	HORIZONTAL TAIL B	VERTICAL TAIL A	VERTICAL TAIL B
AREA, SQ FT	900	276	340	209	230
ASPECT RATIO	10.2	4.93	4.00	1.07	1.60
TAPER RATIO	0.30	0.35	0.35	0.80	0.35
SWEEP	30.5°	31.6°	30.0°	43.5°	35.0°
DIHEDRAL	+3°	−3°	+10°	~	~

*SUPERCRITICAL AIRFOIL

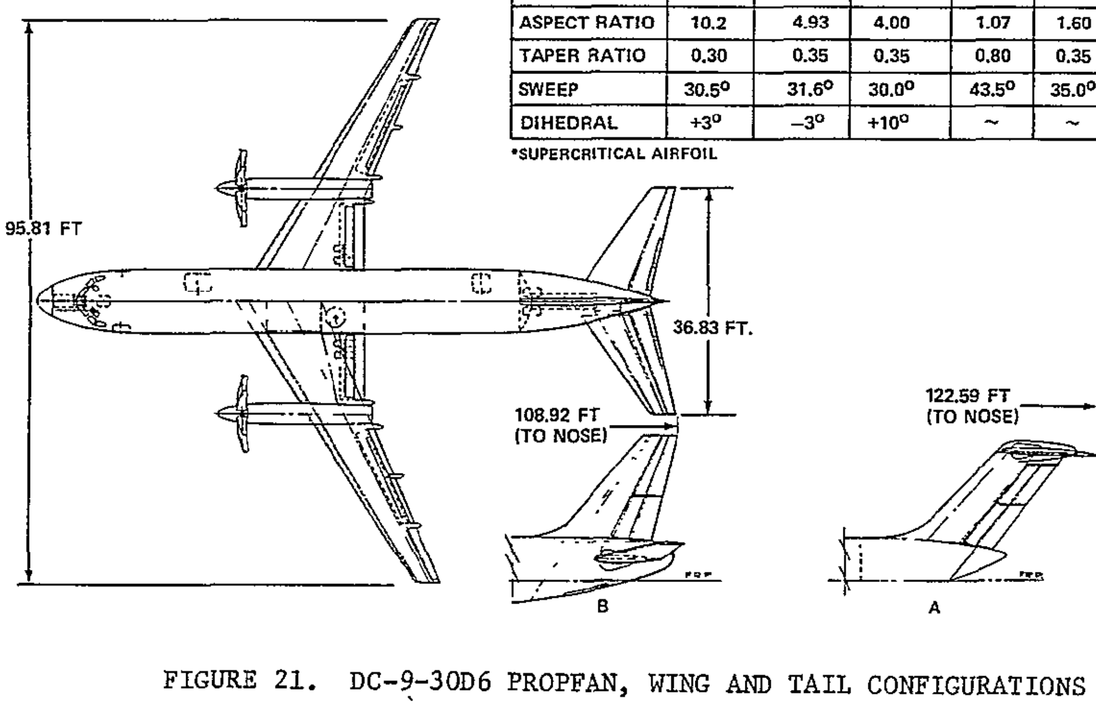


FIGURE 21. DC-9-30D6 PROPFAN, WING AND TAIL CONFIGURATIONS

Performance comparisons were based on the initial choice of a 720 fps rotational tip speed for the propfan, which resulted in a propeller efficiency of 0.73 and an installed cruise TSFC of 0.65 lb/lb/hr. The sensitivity of aircraft performance to propfan efficiency levels was also examined because a higher propfan tip speed (800 fps), together with expected engine improvements, could give an installed cruise TSFC of 0.53 lb/lb/hr. The 720 fps tip speed propfan was chosen for initial design studies because noise levels at the outer fuselage wall would be approximately 5 to 7 dB lower than for a propfan with an 800 fps tip speed.

In Figure 22 the DC-9-30D4, D5, and D6 payload-range capabilities are compared to that of the basic DC-9-30. Range performance with the supercritical wing was attained with outer wing fuel tanks only, while both center section and outer wing fuel tanks were used on the basic DC-9 wing. This results in approximately 3.2% less fuel in the supercritical wing when compared to the basic DC-9 wing.

When the aircraft are not fuel limited, the supercritical wing increases turbofan and turboprop range capability by 9 to 12%. For conditions when the aircraft are fuel limited, the range capability is increased by only 7 to 8%, as a result of the reduced fuel capacity of the smaller supercritical wing.

Compared to the turbofan, the propfan with TSFC = 0.65 increases range 21 to 24% when the aircraft is not fuel volume limited, and 40 to 43% at payload-range points that are fuel capacity limited. With TSFC = 0.53, the DC-9-30D5 propfan range improvement over the DC-9-30 at 58% load factor increases from 41% to 73%.

Figure 23 shows the fuel savings due to the advanced supercritical wing, the propfan propulsion system, and the combination of both. The improvement due to the wing increases as range increases, for either propulsion system, from 6 to 9% at high altitude cruise and from 3 to 5% at low altitude cruise.

For TSFC = 0.65, the propfan fuel savings, shown in Figure 23b, decrease as range increases from 27 to 23% at high altitude cruise and from 30 to 25% at low altitude cruise. This effect is due to the higher rate of climb for propfan aircraft, which gives additional efficiency at short ranges due to higher operating altitudes. The effect of a lower TSFC on fuel savings is also shown in Figure 23b. At an average range of 290 NM, propfan fuel savings increase from 27 to 33%.

8.3 Comparative Aircraft Prices

In order to realistically evaluate the economic viability of the turboprops, consistent aircraft prices and operating costs were developed. All aircraft prices were estimated in 1976 dollars, and then deescalated at 5% per year to 1973 dollars. The turboprop airplanes have a total flyaway cost estimated to be 12% higher than for the turbofan aircraft (Table 40).

DC-9-32 TURBOFAN, PROPFAN AND SCW DERIVATIVES

CRUISE CONDITIONS: Alt = 30,000 Ft, M = .8, TSFC = 0.65 Lb/Lb/Hr

AIRCRAFT	WING	POWERPLANT	OEW	WING AREA	ASPECT RATIO	SWEEP
DC-9-30	DC-9	JT8D-7	57,900	1,001	8.7	24.5
DC-9-30D4	SCW	JT8D-7	58,080	900	10.2	30.5
DC-9-30D5	DC-9	STS476 PROPFAN	61,220	1,001	8.7	24.5
DC-9-30D6	SCW	STS476 PROPFAN	61,400	900	10.2	30.5

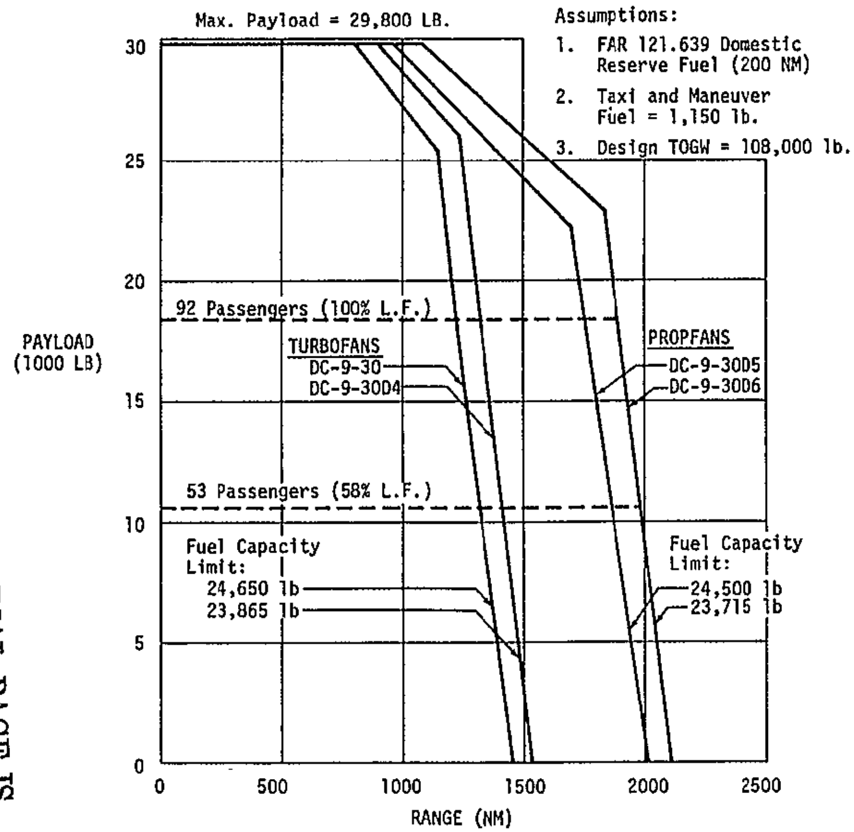


FIGURE 22. PROPFAN PAYLOAD-RANGE COMPARISON

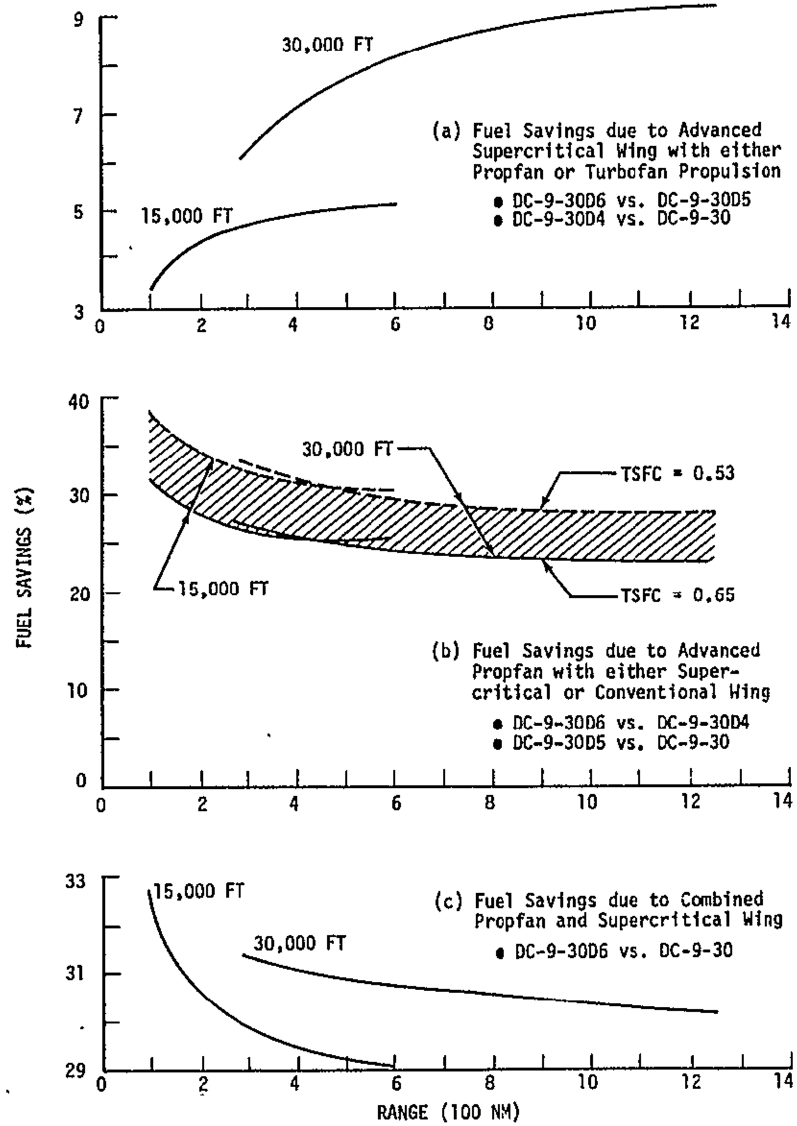


FIGURE 23. COMPARISON OF BLOCK FUEL SAVINGS

TABLE 40

COMPARATIVE AIRCRAFT PRICES
(Millions of 1973 Dollars)

Price Components	DC-9-30 Baseline	DC-9-30D4 Turbofan-SCW	DC-9-30D5 Propfan	DC-9-30D6 Propfan-SCW
Airframe	$4.48	$4.48	$4.48	$4.48
Engines	1.20	1.20	1.47	1.47
Gearboxes & Propfans	—	—	.39	.39
Total Aircraft Price	$5.68	$5.68	$6.34	$6.34

8.4 Direct Operating Costs

The direct operating costs for the four study airplanes were calculated using the 1967 ATA DOC method updated to 1973 cost levels. The assumptions used in determining DOC's were the same for both the turbofan and turboprop aircraft. Since possible turboprop maintenance expense benefits from reductions in the maintenance of brakes, tires, and wheels as well as possible turboprop gearbox maintenance cost penalties had not been determined, they were not included in the DOC's.

The DOC's for the study aircraft were calculated at various stage lengths using fuel prices of 30¢ and 60¢ per gallon. Although the turboprop airplanes appear to be slightly more expensive initially than comparable turbofans, fuel savings of between 27 and 33% allow the turboprops to offer DOC savings of 5-6% with fuel at 30¢ per gallon and 9-10% at 60¢ per gallon, as shown in Table 41. Possible maintenance benefits could increase these savings slightly. The DOC benefit derived from the incorporation of a supercritical wing on a turboprop is also shown in the table.

TABLE 41

DOC SAVINGS OF TURBOPROP AIRCRAFT RELATIVE TO COMPARABLE TURBOFANS

Aircraft Comparisons	CAB Average Stage Length (290 NM)		1,000 NM	
	30¢/Gal	60¢/Gal	30¢/Gal	60¢/Gal
DC-9-30D5 Propfan vs. DC-9-30 Turbofan	5.5	9.9	5.8	10.4
DC-9-30D6 Propfan (SCW) vs. DC-9-30D4 Turbofan (SCW)	5.1	9.5	5.0	9.4
DC-9-30D6 Propfan (SCW) vs. DC-9-30D5 Propfan	1.4	2.2	2.5	3.7

SECTION 9.0

CONCLUSIONS AND RECOMMENDATIONS

9.1 Study Conclusions

9.1.1 Technology Conclusions

For the baseline aircraft, actual airline seat-mile fuel efficiency is an average of 30.2% below the engineering values derived for ideal conditions at the 1973 CAB average stage lengths. Differences in actual values are caused by greater air holding and ground delay times, clearances to non-optimum altitudes, winds, high temperatures, engine and airframe deterioration, and excess fuel loads.

The results of the technical analysis of various fuel-saving options are summarized in Table 42. The range of possible fuel savings shows that opportunities for fuel savings vary widely from aircraft to aircraft. For a given option, the low value corresponds to the lowest fuel saving for any aircraft, and the high value corresponds to the greatest saving for any aircraft.

TABLE 42

FUEL SAVINGS SUMMARY - U.S. DOMESTIC AIRCRAFT

Fuel-Saving Option	Range of Possible Fuel Savings (%)
OPERATIONS	4 - 30
- Flight	4 - 11
- Airline	5 - 13
MODIFICATIONS	4 - 28
- Retrofit	4 - 28
- Production	10
DERIVATIVES	4 - 28
NEW NEAR-TERM AIRCRAFT	10 - 41
- Relative to Existing Narrow Body	20 - 41
- Relative to Existing Wide Body	10 - 33
PROPFAN DC-9	27 - 33

9.1.2 Market Conclusions

The most important conclusions that can be drawn from the fleet forecasts about the relative importance of each of the fuel saving options in reducing the fuel consumption of the U.S. domestic and international air transportation system during 1973-1990 are:

- o Fuel conserving flight procedures offer important immediate fuel savings, many of which have already been implemented.
- o Additional fuel savings could be obtained operationally through the development and implementation of improved domestic and international ATC systems.
- o Higher load factors would improve fuel efficiency substantially in a static airline environment.
- o Aerodynamic retrofits appear to be worth pursuing in terms of fuel savings and modest economic gains for a short interim period.
- o Reengining older narrow body aircraft for saving fuel is too expensive to be a viable fuel conserving alternative.
- o Derivatives of current airplanes, sized to meet the future needs of the U.S. domestic and U.S. international markets, would offer significant fuel savings as well as improved economics over the baseline airplanes as well as modifications of current aircraft.
- o The derivative aircraft were the most promising options in terms of fuel conservation as well as economic viability in both markets for the near term.
- o The all-new (N80) domestic aircraft offer the greatest potential for fuel savings and improved economics in the far term, beyond 1985-1990. However, the N80 international aircraft did not offer the potential for fuel savings that the domestic N80's did during the same study period.
- o The preliminary investigation of an advanced technology turboprop indicated significant fuel savings as well as considerable economic promise for an advanced turboprop as a replacement for the current DC-9/B737 aircraft types.

9.2 Recommendations

- o Expand the study of fuel-conservative flight operations to include all aircraft types in the domestic fleet, and to include a wider scope of operational variations. The study results should be specific to each airline's market, fleet, and schedule.
- o Evaluate the potential fuel savings benefits accruing from an improved air traffic control system weighed against the total costs of improving the system.

- Study the costs and benefits of optimum cruise control, which would allow an aircraft to accurately follow a minimum-fuel flight profile within the mission and ATC system constraints.

- Perform an ATC system study in order to identify ways to reduce the constraints on minimum-fuel flight profiles.

- Investigate the potential fuel savings benefits of reducing fuel reserve requirements for the U.S. air transportation system under an improved ATC system.

- Continue the study and testing of winglets as a possible means of reducing the wing spans of future new transports designed for minimum DOC at high fuel prices.

- Study folding wing tips as an alternative approach for reducing wing spans in the airport terminal area.

- Continue the theoretical and experimental development of supercritical airfoil technology and three-dimensional applications.

- Study the contouring of aircraft surfaces to achieve more extensive natural laminar flow.

- Continue studies of active controls technology, including the use of active controls on derivatives of in-production aircraft.

- Study aeroelastic effects on the weight of very high aspect ratio transport wings.

- Demonstrate the full scale use of composite primary structure in transport aircraft.

- Conduct studies to improve the integration of high-bypass-ratio turbofan powerplants with airframes.

- Develop methodology to effectively evaluate, from an airline's viewpoint, the economic potential of retrofitting current generation aircraft to conserve fuel.

- Examine the effects of striving for higher load factors, as a means to reduce aircraft fuel consumption, on forecasted market demand and service frequencies.

- An in-depth study of traffic demand, jet fuel prices, and fare levels, as well as their interreactions, to estimate the future elasticity of air travel demand in the U.S. domestic air transportation system.

- Evaluate the fuel conserving potential and applicability of a smaller N80 airplane (125-150 seats) with a design range of 1500 nautical miles for the U.S. domestic air transportation system.

- Size and design an all-new aircraft specifically for the operations of the U.S. international carriers optimizing the designs for minimum DOC's at several fuel prices and minimum fuel consumption. Assess the fuel saving potential and economic viability of this airplane family in simulated international operations. The sizing of this airplane should begin with a seating capacity of approximately 150-175 seats and a design range of 5000-5500 nautical miles.

- Develop a broader spectrum of study engines for propfan applications.

- Conduct tests to verify theoretical propfan efficiency and noise levels.

- Study the effects of the propfan slipstream on airframe aerodynamics and also on noise and vibration in tail surfaces and the aft fuselage.

- Investigate propfan aircraft flight profiles, including takeoff performance and the effects of cruise altitude and Mach number on fuel use.

- Expand the study of DC-9 turboprop aircraft to examine the benefits from and costs of other advanced technologies when applied to this type of airplane.

- Conduct a comparative market and economic analysis to determine the operational and economic performance of turboprop aircraft versus comparable turbofan aircraft over the same selected airline network.

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AMERICAN REVOLUTION BICENTENNIAL 1776-1976

REPLY TO ATTN OF: NAS2-8618
AT:241-12-02

November 7, 1977

NASA Representative
Scientific & Technical Information Facility
P. O. Box 8757
Baltimore/Washington International Airport,
Maryland 21240

Subject: Transmittal of Contractor Report: "Cost Benefit Tradeoffs for Reducing the Energy Consumption of the Commercial Air Transportation System," dated June 1976, by E. F. Kraus and J. C. Van Abkoude, Douglas Aircraft Company, McDonnell Douglas Corporation

Reference: Program Code 791-40-03

The subject report prepared under Contract NAS 2-8618 has been reviewed at Ames and is recommended for release in STAR as CR-137925.

Paul Bennett

Paul Bennett
Chief, Technical Information Division

Enclosure:
1 Cy Subject Report

cc:
NASA Hqrs., Code KSI (w/o enclosure)